N*'s as determined from exclusive reactions

Volker D. Burkert

Outline:

- Goals of the N* Program
- Large Acceptance Detectors
- N* related data from JLab
- Status of the N* Analysis
- Upcoming experiments at Jlab @ 6 GeV
- Tools for more complex analyses
- Penta-Quarks and N*'s
- Conclusions

Goals of the N* Program

Two main motivations for the N* program:

- The study of the nucleon wave function though measurement of e.m. transition form factors for known resonances, e.g. $\Delta(1232)$, $P_{11}(1440)$, $S_{11}(1520)$, $D_{13}(1520)$, $F_{15}(1680)$, ...
  => analyze $N\pi$, $N\eta$, $(N\pi\pi)$ final states

- The study of the underlying symmetry properties through the search for SU(6)xO(3) symmetry predicted, yet undiscovered resonances ("missing resonance problem"), in measurements of $N\pi$, $N\pi\pi$, $K^+\Lambda$, $K^+\Sigma$, $p\omega$, $N\rho$, .. final states.

Large Acceptance Detectors for N* Physics.

CLAS: (photon and electron reactions)

- Measure many final states with mostly charged particles simultaneously.
- Operate with high luminosity electron beams, and with unpolarized and polarized energy-tagged bremsstrahlung photon beams.
- Coverage for photons limited to lab angles < 45^o

Crystal Barrel-ELSA: (photon reactions)

- CsI with excellent photon detection, e.g. $N\pi^o\pi^o$, $N\pi^o\eta$

SAPHIR-ELSA (photon reactions, detector dismantled)

- Charged particles in final state

GRAAL (photon reactions):

- BGO crystals, with excellent photon detection, limited charged particle, polarized laser-backscattered tagged photon

Crystal Ball – MAMI (photon reactions)

neutral final states in limited W range

BES (Beijing) – N* in e^+e^- collisions.

LEPS – SPring-8 – (photon reactions)

- Charged particle detection in forward dipole spectrometer, and TPC with large angle coverage.

Status of N*- exclusive meson production

Experiment	Reaction	Physics	Data Status	Analysis Status	Publication Status
E89-037	$ep \rightarrow ep\pi^o$	R_{EM}, R_{SM}	compl.	ongoing	PRL88, 122001 (2002)
	$ep \rightarrow en\pi^+$	R_{EM}, R_{SM}	compl.	ongoing	in preparation
E89-038	$ep \rightarrow en\pi^+$	γpN^*	compl.	ongoing	in preparation
	$eD \rightarrow ep\pi^-$	γnN^*	compl.	---	---
E89-039	$ep \rightarrow ep\eta$	γNS_{11}	compl.	ongoing	PRL86, 1702 (2001)
E89-042	$\vec{e}p \rightarrow ep\pi^o$	$\sigma_{LT'}$, $N\Delta$	compl.	ongoing	PRC68, 032201 (2003)
	$\vec{e}p \rightarrow en\pi^+$	$\sigma_{LT'}$, $N\Delta$	compl.	ongoing	in CLAS review
E01-102	$ep \rightarrow ep\pi^o$	$\sigma_{LT'}$, NN^*	compl.	ongoing	---
E01-103	$ep \rightarrow en\pi^+$	$\sigma_{LT'}$, NN^*	compl.	ongoing	---
E91-002	$ep \rightarrow ep\pi^o$	R_{EM} high Q^2	compl.	ongoing	in preparation
E99-107	$ep \rightarrow ep\pi^o$	R_{EM} high Q^2	compl.	ongoing	---
E91-024	$ep \rightarrow ep\omega$	miss. N*	compl.	ongoing	---
E93-006	$ep \rightarrow ep\pi^+\pi^-$	miss. Res.	compl.	ongoing	PRL91, 022002 (2003)
E99-108	$\vec{e}p \rightarrow ep\pi^+\pi^-$	miss. Res.	compl.	started	---
E93-036	$\vec{e}\vec{p} \rightarrow ep\pi^o$	A_{et}, A_t	compl.	ongoing	PRC68, 035202 (2003)
	$\vec{e}\vec{p} \rightarrow e\pi^+n$	A_{et}	compl.	compl.	PRL88, 82001 (2002)
E93-030	$ep \rightarrow eK^+\vec{\Lambda}$	N*, miss N*	compl.	ongoing	PRL90, 131804 (2203)
E94-005	$ep \rightarrow ep\pi^+\pi^-$	Axial ff	compl.	ongoing	---
E91-023	$ep \rightarrow eX$	A_{et}	compl.	ongoing	PRL91, 222002 (2003)

Status of N*- exclusive meson production

Experiment	Reaction	Physics	Data Status	Analysis Status	Publication Status
E00-112	$\vec{e}p \rightarrow eK^+\vec{\Lambda}$	miss. N*	compl.	ongoing	PRL90, 131804
E91-011	$\vec{e}p \rightarrow e\vec{p}\pi^0$	R_{EM},R_{SM}	compl.	ongoing	in preparation
E93-050	$ep \rightarrow ep\gamma(\pi^0)$	N*	compl.	compl.	nucl-ex/0308009
E94-014	$ep \rightarrow ep\pi^0$	NΔ(1232)	compl.	compl.	PRL82:45 (1999)
	$ep \rightarrow ep\eta$	S_{11}(1535)	compl.	compl.	PRD60:052004 (1999)

Status of N*- exclusive meson production

Experiment	Reaction	Physics Status	Data Status	Analysis Status	Publication
E89-004	$\gamma p \to K^+Y$	miss. N*	compl.	ongoing	nucl-ex/0305028
E91-008	$\gamma p \to p\eta$	S_{11}, P_{11}	compl.	compl.	PRL89, 222002
E93-033	$\gamma p \to p\pi^+\pi^-$	miss. N*	compl.	ongoing	in prep.
E94-008	$\gamma D \to \eta X$	N*	compl.	ongoing	-
E94-103	$\gamma p \to N\pi$	N*	compl.	ongoing	-
E94-109	$\gamma p \to p\rho^o$	miss. N*	ongoing	ongoing	-
E99-013	$\vec{\gamma}\, p \to p\omega$	miss. N*	ongoing	ongoing	-
E02-112	$\vec{\gamma}\, \vec{p} \to K^+Y$	miss. N*	tbd	-	-
E03-105	$\vec{\gamma}\, \vec{p} \to \pi N$	N*	tbd	-	-

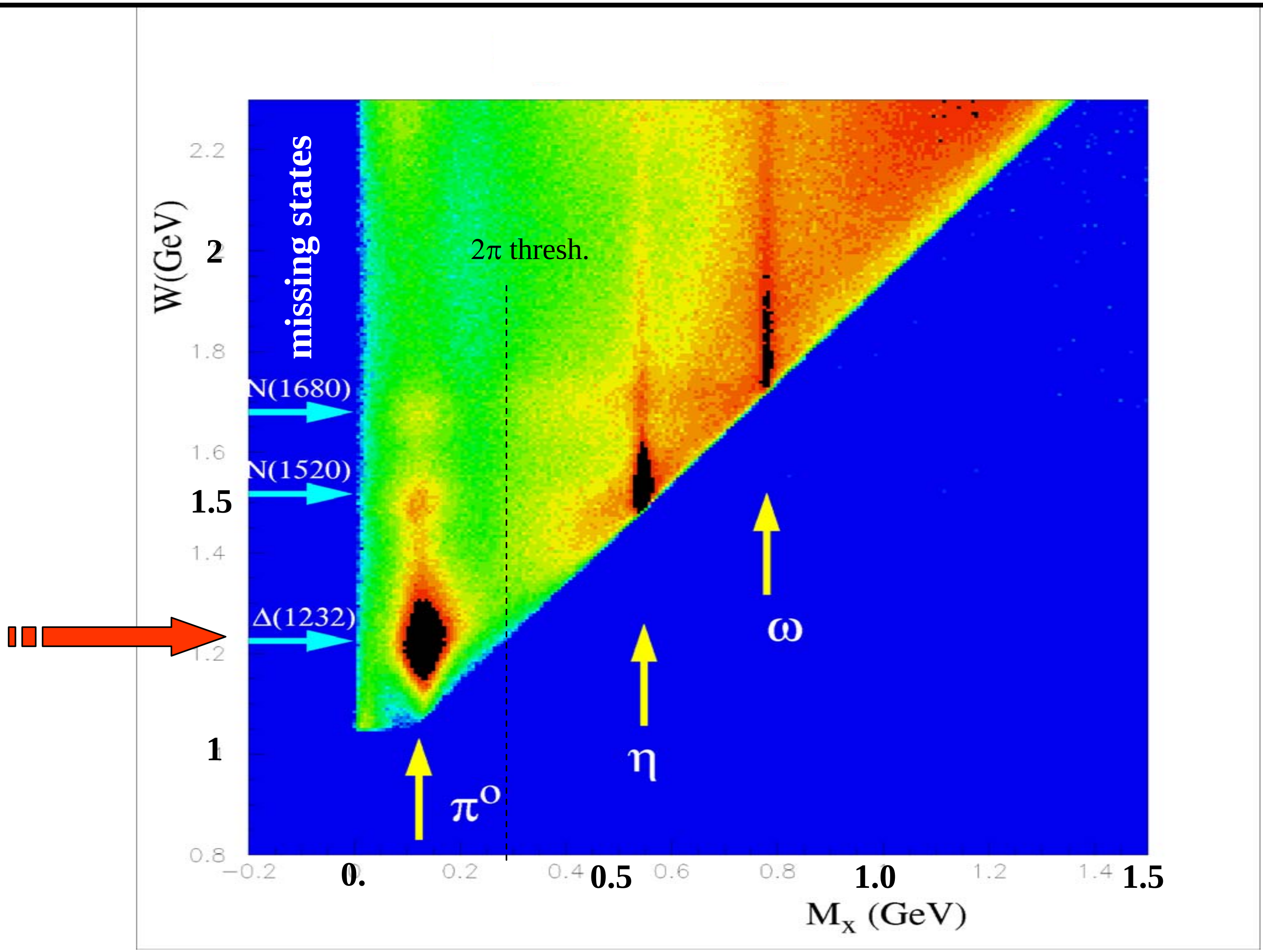
Penta-Quark Baryons and N* Physics

E03-	$\gamma d \to K^+K^-p(n)$	5-quark B5	sched.	ongoing	PRL91, 252001(2003)
E05-xxx	$\gamma p \to K^+K^-\pi^+(n)$ K^0nK^+	5-quark B5	sched.	ongoing	PRL92, 01 (2004)

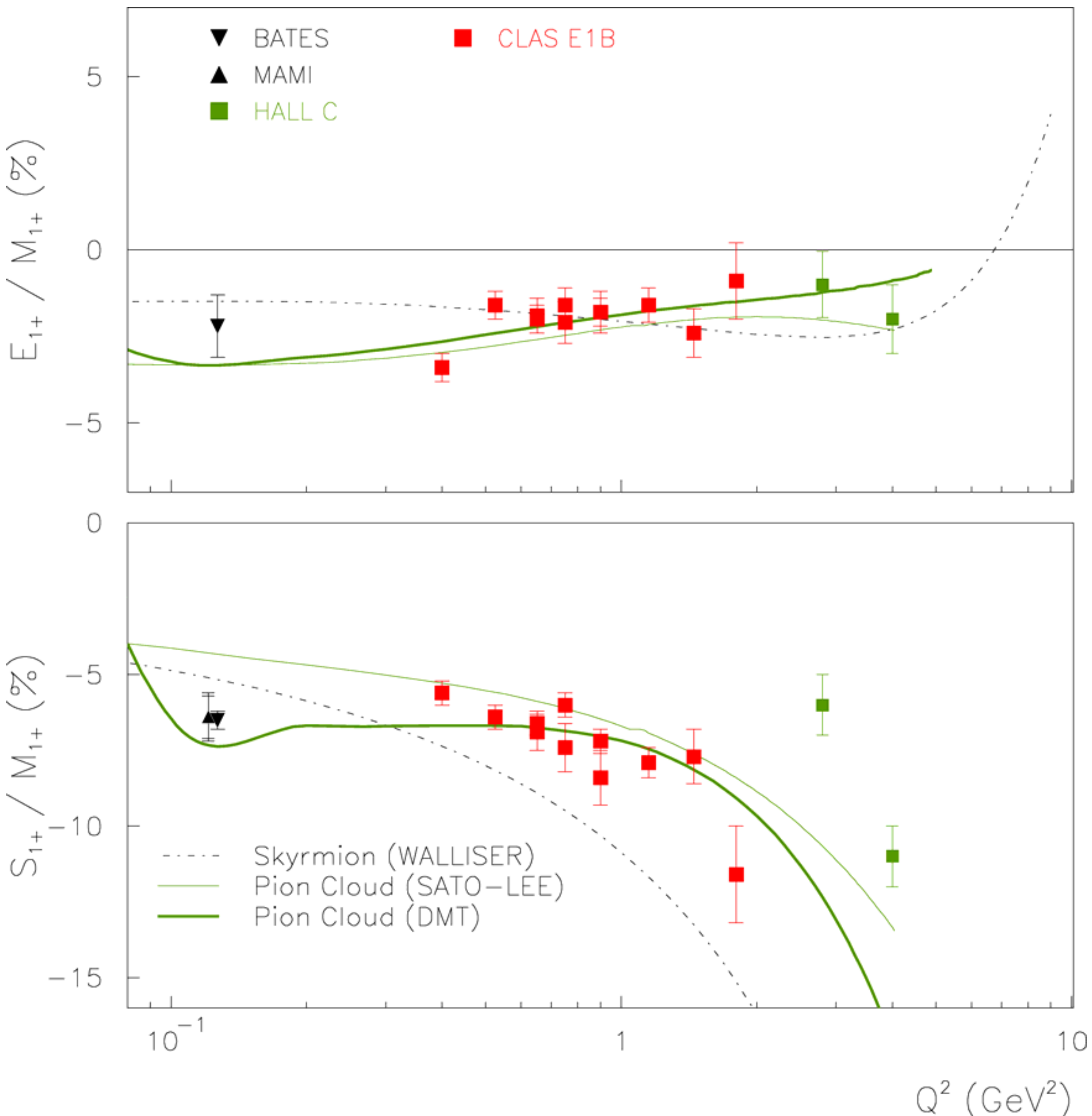
Status of N*- exclusive meson production

---	γd	$\rightarrow K^+K^-p(n)$	5-quark B5	---	ongoing	PRL91, 252001(2003)
E03-xxx				sched	---	---
---	γp	$\rightarrow K^+K^-\pi^+(n)$	5-quark B5	---	ongoing	PRL92, 01 (2004)
E04-xxx		$\rightarrow K^o n K^+$, ..	Excited Θ^+	sched.	---	---
E04-xxx	ed	$\pi^-\pi^-\pi^-p$	Search for X^{--}	tbd	---	---
E04-xxx	ep	many	Θ^+, Ξ^{--}	tbd	---	---

Kinematics $ep \longrightarrow epX$, E=4GeV



NΔ(1232) Transition



- Data published after 1998

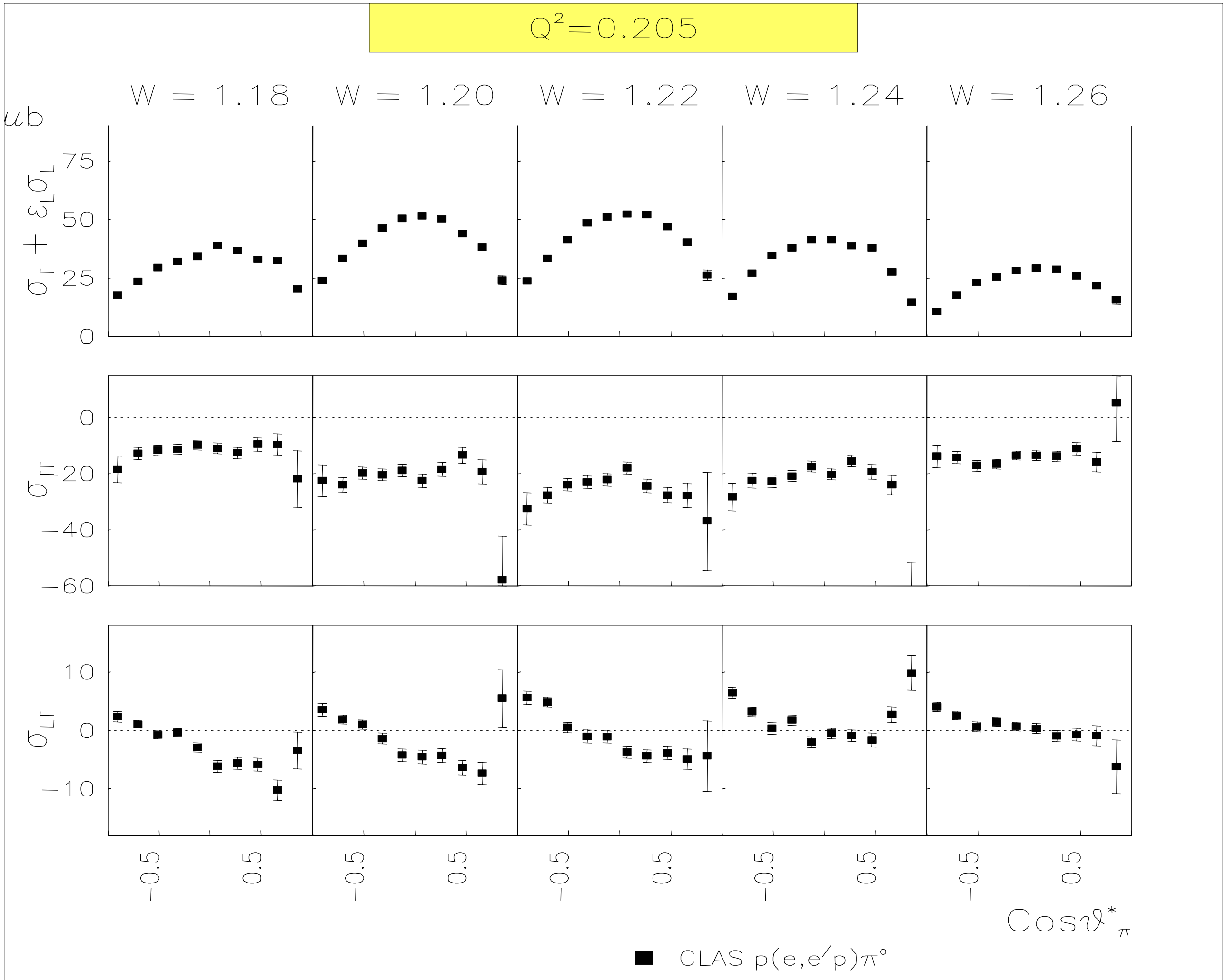
NΔ(1232) – current program

(data in hand, partially analyzed)

- $p\pi^0$ with high statistics are currently being analyzed covering $Q^2 = 0.1 – 6.0$ GeV^2
- $ep \longrightarrow e\pi^+ n$ channel for $Q^2 = 0.1 – 6.0$ GeV^2
- Data on $\sigma_{LT'}$ for $p\pi^o$, $n\pi^+$ in $\Delta(1232)$ region at $Q^2 < 4$ GeV^2
- Data on A_t , A_{et} for $p\pi^o$, $n\pi^+$, $p\pi^-$ at $Q^2 < 4$ GeV^2
- Single and double polarization resp. functions – at $Q^2 = 1$ GeV^2
- Cross section for $p\pi^0$ at backward π^0 angles – at $Q^2 = 1$ GeV^2
- $p\pi^0$ with high statistics taken at $Q^2 = 6.0$ & 7.5 GeV^2

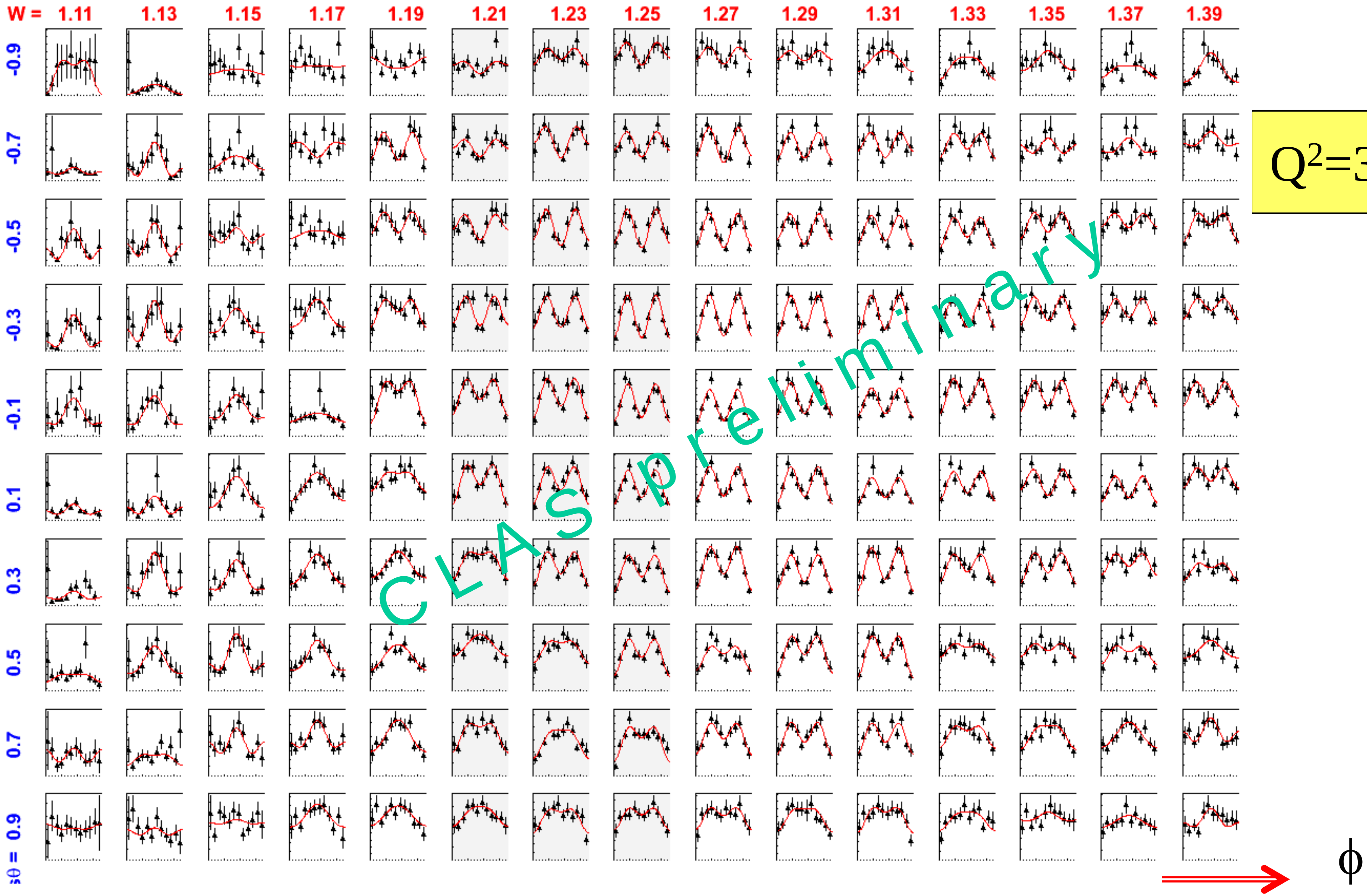
Response Functions from π^0 Electroproduction in the $\Delta(1232)$ Region

$$d\sigma/d\Omega = \sigma_T + \varepsilon\sigma_L + \varepsilon\sigma_{TT}\cos 2\phi + \sqrt{2\varepsilon(\varepsilon+1)}\sigma_{LT}\cos\phi; \qquad \sigma_i(\cos\theta^*, W)$$



CLAS Preliminary

N* program – NΔ(1232) transition

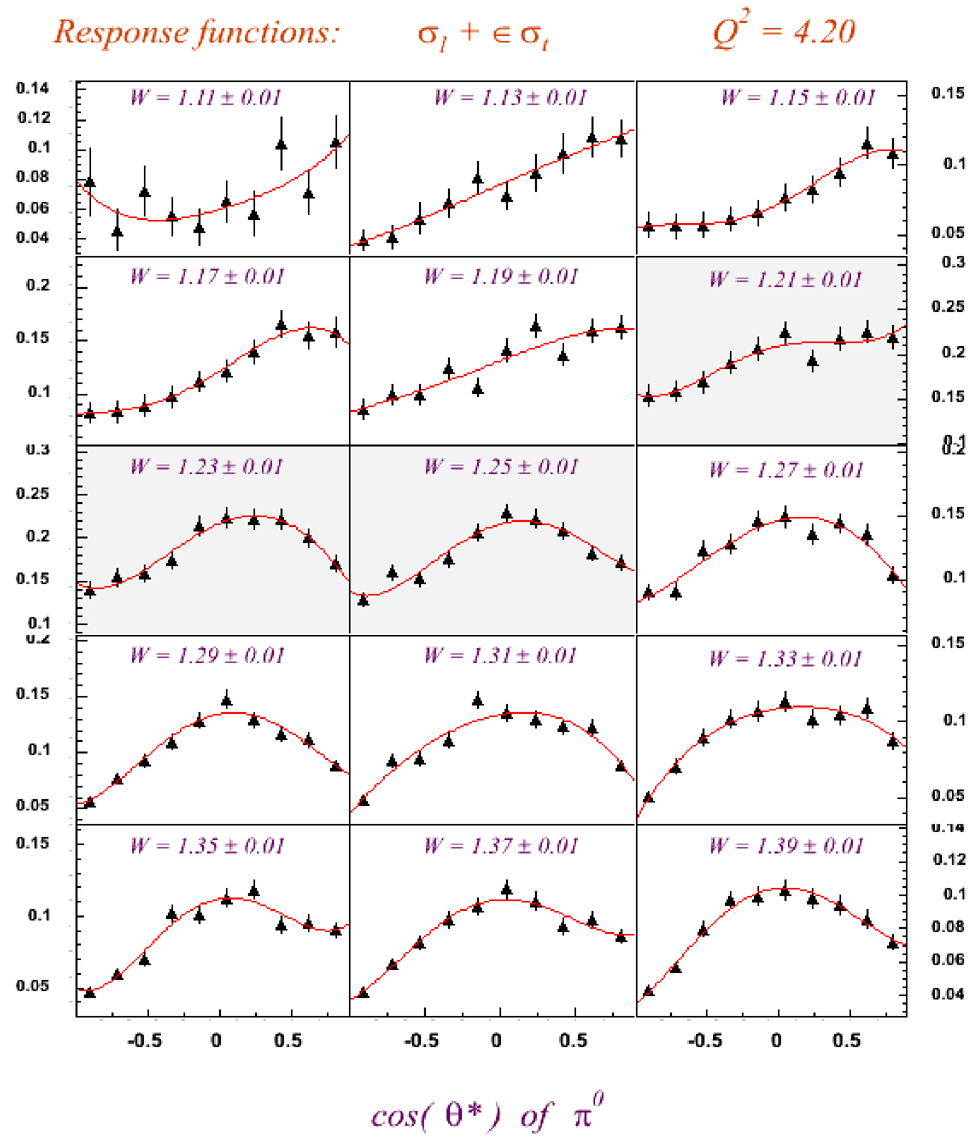


Q^2=3GeV^2

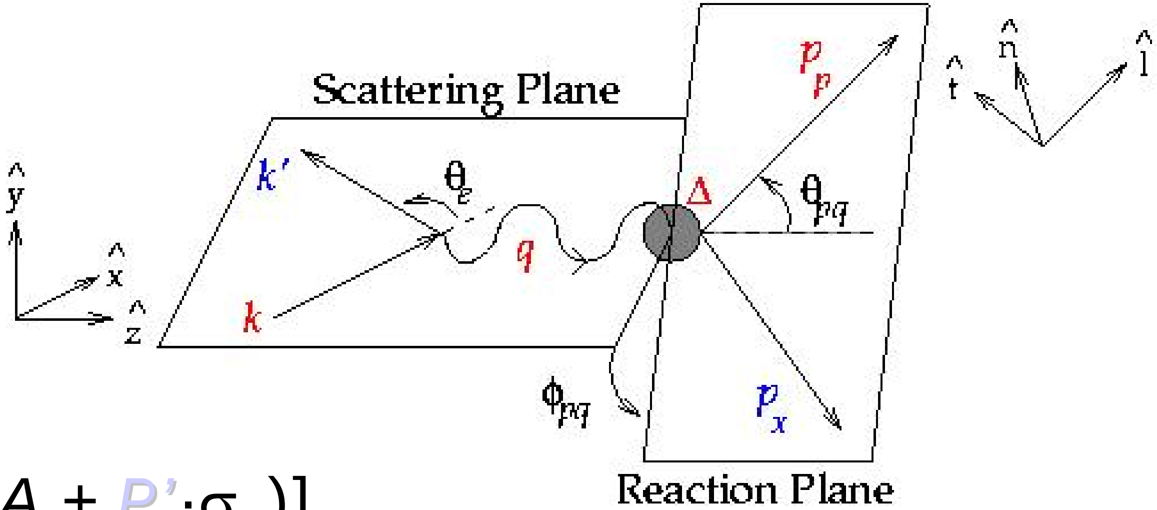
NΔ(1232) Transition

$$\sigma_T + \varepsilon\sigma_L = A_0 + A_1 P_1(\cos\theta) + A_2 P_2(\cos\theta) + A_3 P_3(\cos\theta) + A_4 P_4(\cos\theta)$$

CLAS preliminary



Polarization Observables



$$\sigma = \sigma_o[1 + P\cdot\sigma_p + h(A + P'\cdot\sigma_p)]$$

$$\sigma_o = \nu_o(\nu_L R_L + \nu_T R_T - \nu_{LT} R_{LT} \cos\phi_{pq} + \nu_{TT} R_{TT} \cos 2\phi_{pq})$$

$$A\sigma_o = \nu_o(-\nu'_{LT} R'_{LT} \sin\phi_{pq})$$

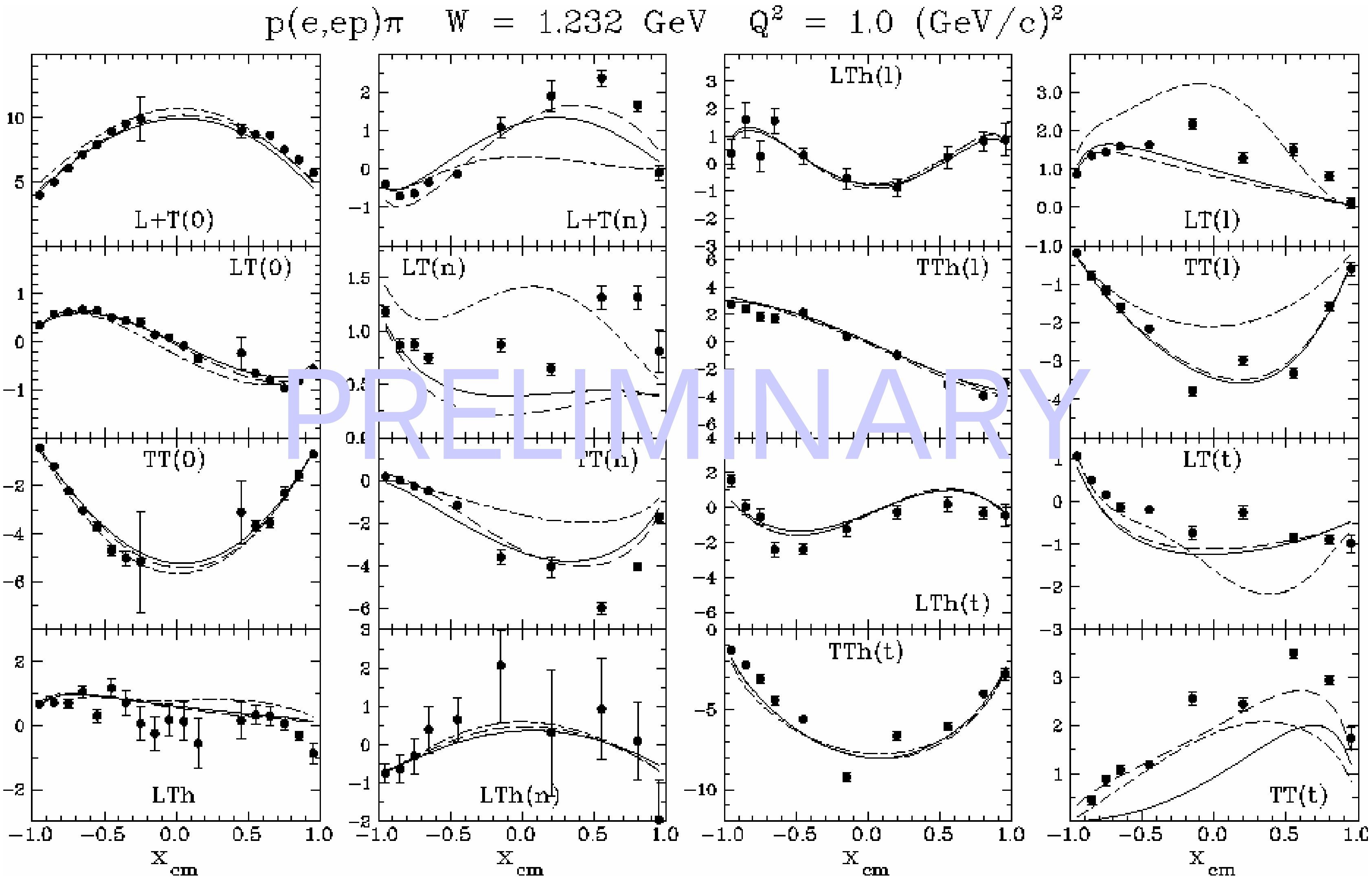
$$P_n\sigma_o = \nu_o(\nu_L R^n_L + \nu_T R^n_T - \nu_{LT} R^n_{LT} \cos\phi_{pq} + \nu_{TT} R^n_{TT} \cos 2\phi_{pq})$$

$$P_{l,t}\sigma_o = \nu_o(-\nu_{LT} R^{l,t}_{LT} \sin\phi_{pq} + \nu_{TT} R^{l,t}_{TT} \sin 2\phi_{pq})$$

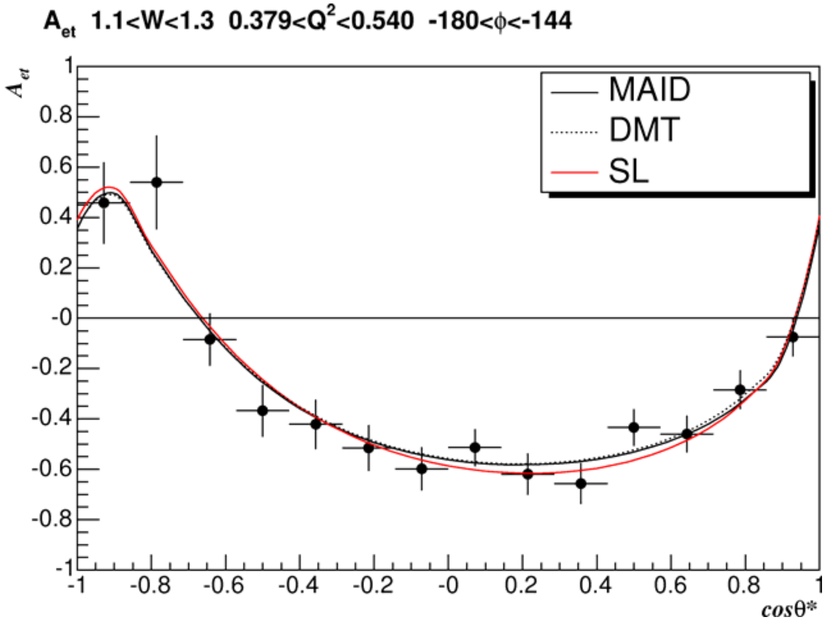
$$P'_n\sigma_o = \nu_o(-\nu'_{LT} R'^n_{LT} \sin\phi_{pq})$$

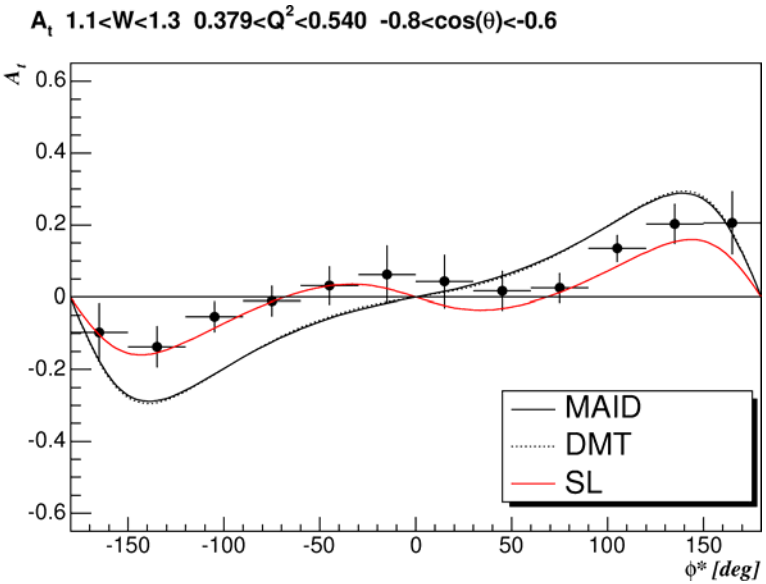
$$P'_{l,t}\sigma_o = \nu_o(-\nu'_{LT} R'^{l,t}_{LT} \cos\phi_{pq} + \nu'_{TT} R'^{l,t}_{TT})$$

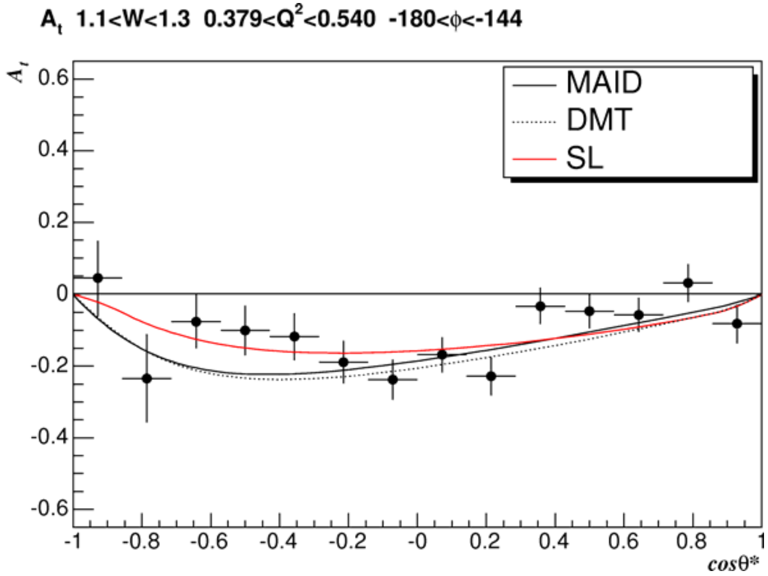
Response Functions – ***Hall A***



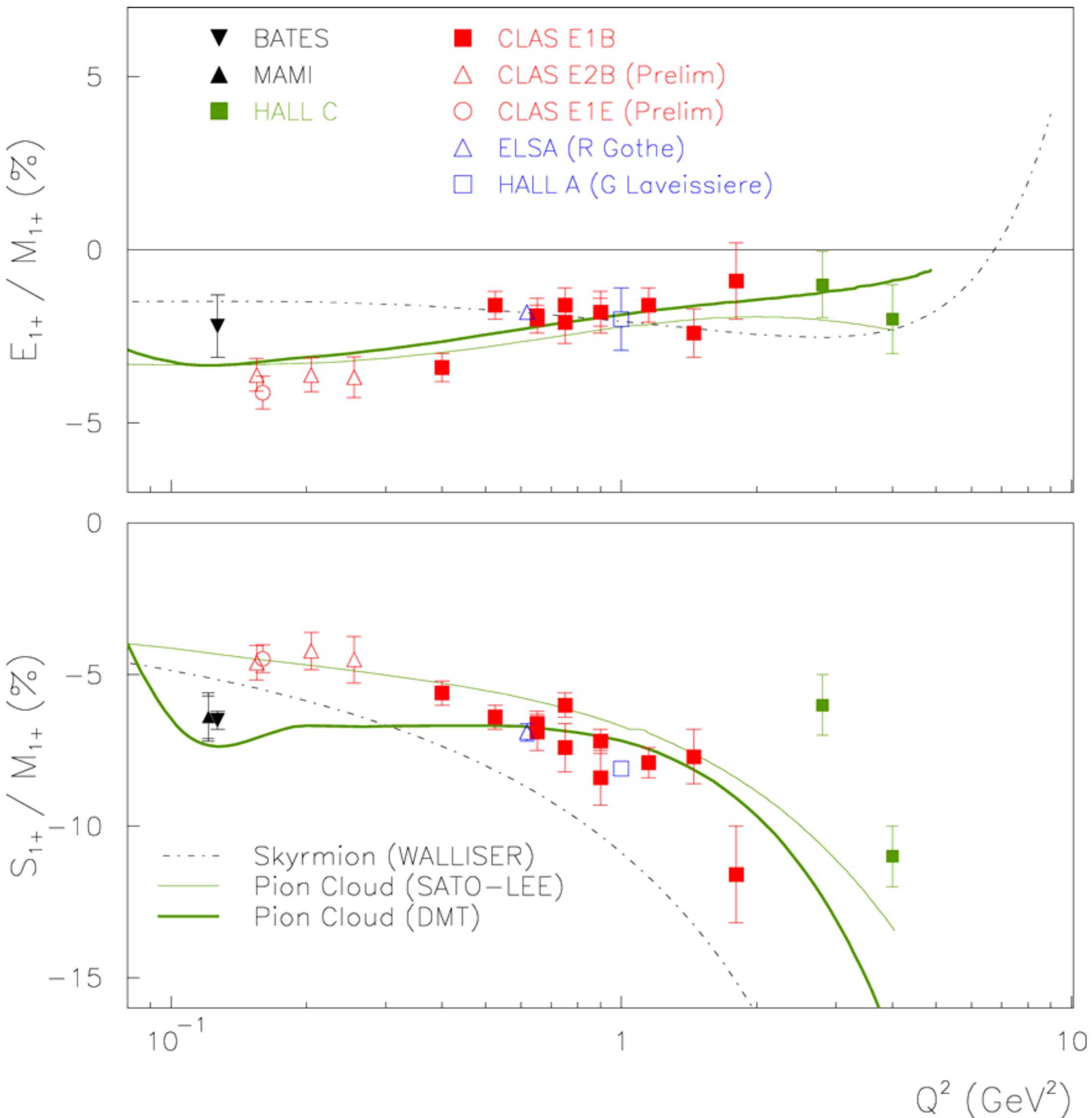
CLAS NΔ(1232) – Asymmetries





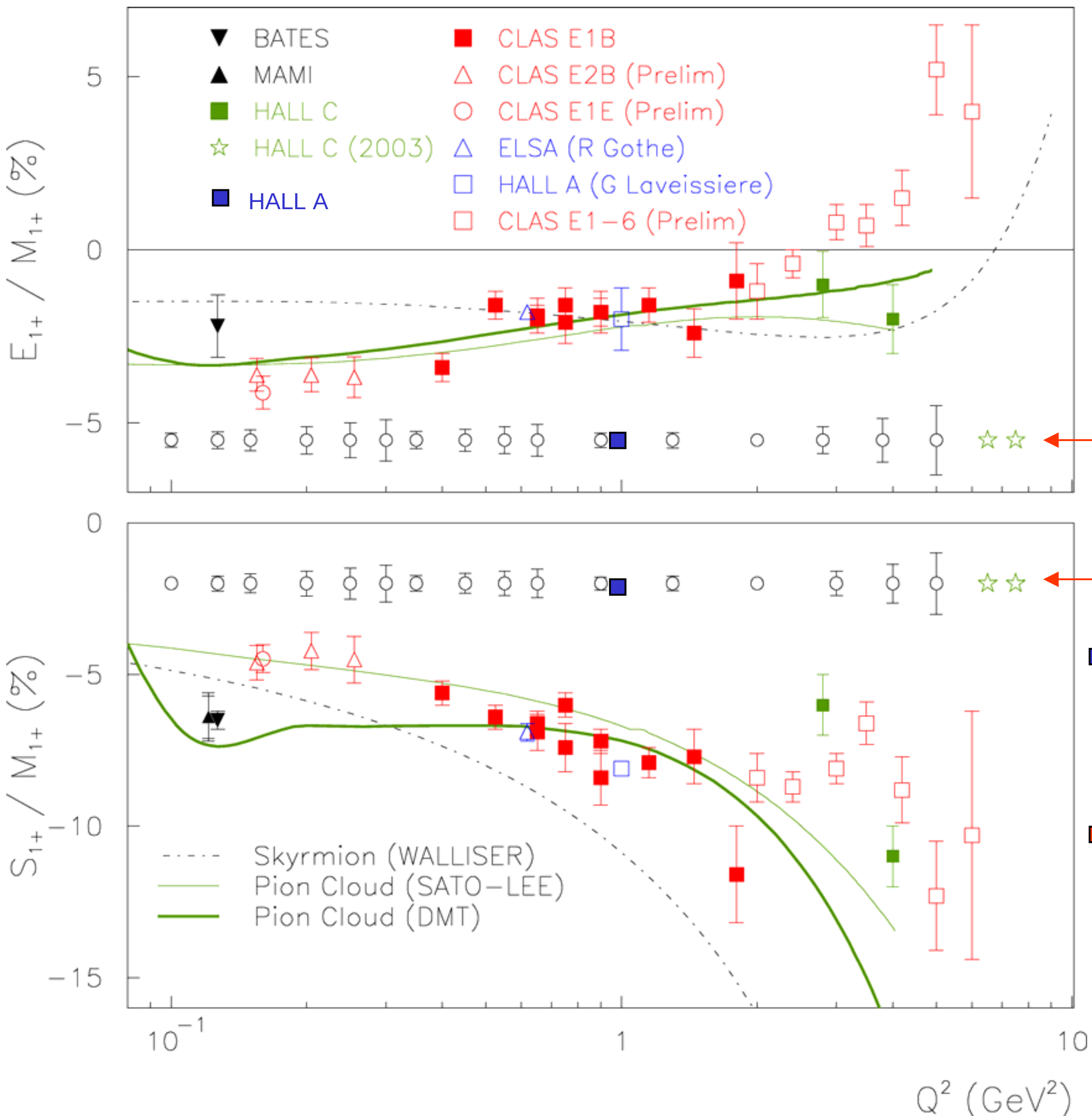


NΔ(1232) Transition



- Published + publicly presented data.

NΔ(1232) Transition



- With current data from CLAS, Hall A & Hall C, JLab data on R_{EM}, R_{SM}, and G_M^D will cover the range $Q^2 = 0.1 – 7.5$ GeV^2 with excellent statistics and low systematics.

Results projected from completed experiments.

- Hall A data include recoil and double polarization responses.

- CLAS data include $p\pi^0$, $n\pi^+$, beam asymmetries A_e, beam/target asymmetries A_t, A_{et}

Analysis Tools for Meson Production above the $\Delta(1232)$

- Unitary Isobar Model (JLab-Yerevan) for single π, η production
  - Born terms + ω, ρ exchange
  - Resonances as relativistic Breit-Wigner
  - Regge exchange at high W

- Fixed- t Dispersion Relations (JLab-Yerevan)
  - Imaginary part of amplitude as sum of Resonances
  - Real part by dispersion relations
  - High energy behavior by Regge parametrization

- Isobar Model for two-pion analysis (JLab-Moscow-Genova)
  - Non-resonant 3-body p.s., diffractive $N\rho$, $\Delta\pi$, $D_{13}\pi$, Reggeon exchange at high W, s-channel Breit-Wigner resonances

- Event-based Partial-Wave Analysis with Maximum-Likelihood fits for $N\pi\pi$ final state (RPI-JLab)

Second Nucleon Resonance Region

Resonances: P_{11}(1440), S_{11}(1535), D_{13}(1520)

- Structure of the Roper P_{11} ?
  - $|Q^3\rangle$ quark state?
  - $|Q^3G\rangle$ state?
  - $|N\sigma\rangle$ molecule?
  - $|Q^4\overline{Q}\rangle$ penta-quark?
  - quark core with meson cloud
- Structure of the S_{11}(1535)
  - hard transition form factor?
  - a 3-quark resonance?
  - a $\overline{K}\Sigma$ molecule?
- Q^2 evolution of the D_{13} helicity structure, $A_{3/2} \rightarrow A_{1/2}$ dominance.

Second Nucleon Resonance Region

- Single pion and eta production

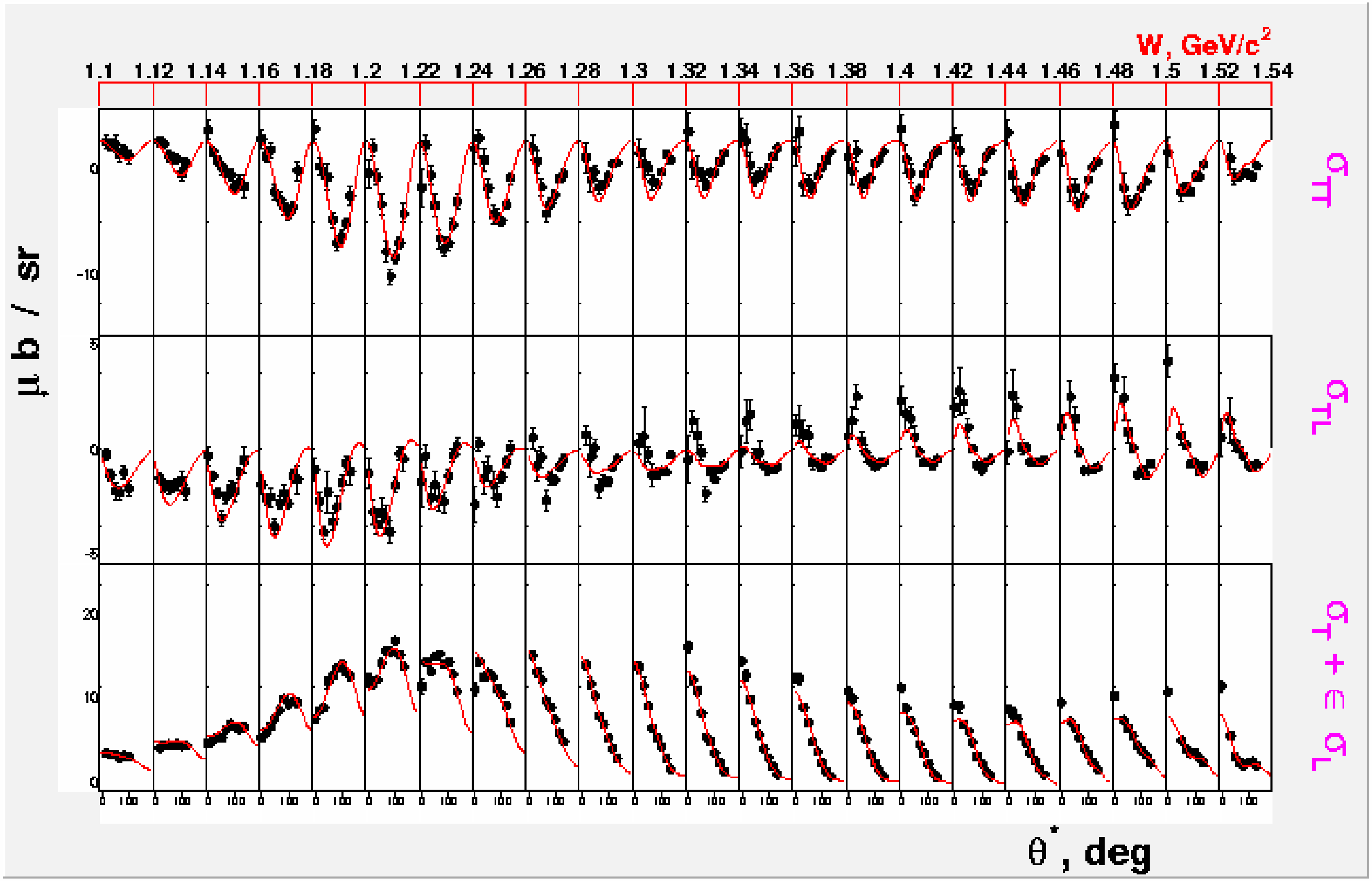
1) $\vec{e}p \longrightarrow e(n\pi^+, p\pi^o)$,	$Q^2 = 0.1 - 5.0\ GeV^2$	E89-038,42 E1-6
2) $\vec{e}d \longrightarrow ep\pi^-(p)$	$Q^2 = 0.1 - 3.5\ GeV^2$	E89-038/42
3) $\vec{e}p \longrightarrow ep\eta$	$Q^2 = 0.1 - 5.0\ GeV^2$	E89-039
4) $\vec{e}\vec{p} \longrightarrow ep\pi^o$	$Q^2 = 0.1 - 3.5\ GeV^2$	E93-036
5) $\vec{e}\vec{p} \longrightarrow e\pi^+n$	$Q^2 = 0.1 - 3.5\ GeV^2$	E93-036

- Global analysis using DR (JLab-Yerevan) and UIM (JLab-Yerevan) fits performed for 1) - 3) at low Q^2 .

- First analysis of a consistent set of π^0, π^+, η cross sections and polarized beam structure functions.

The 2nd Resonance Region

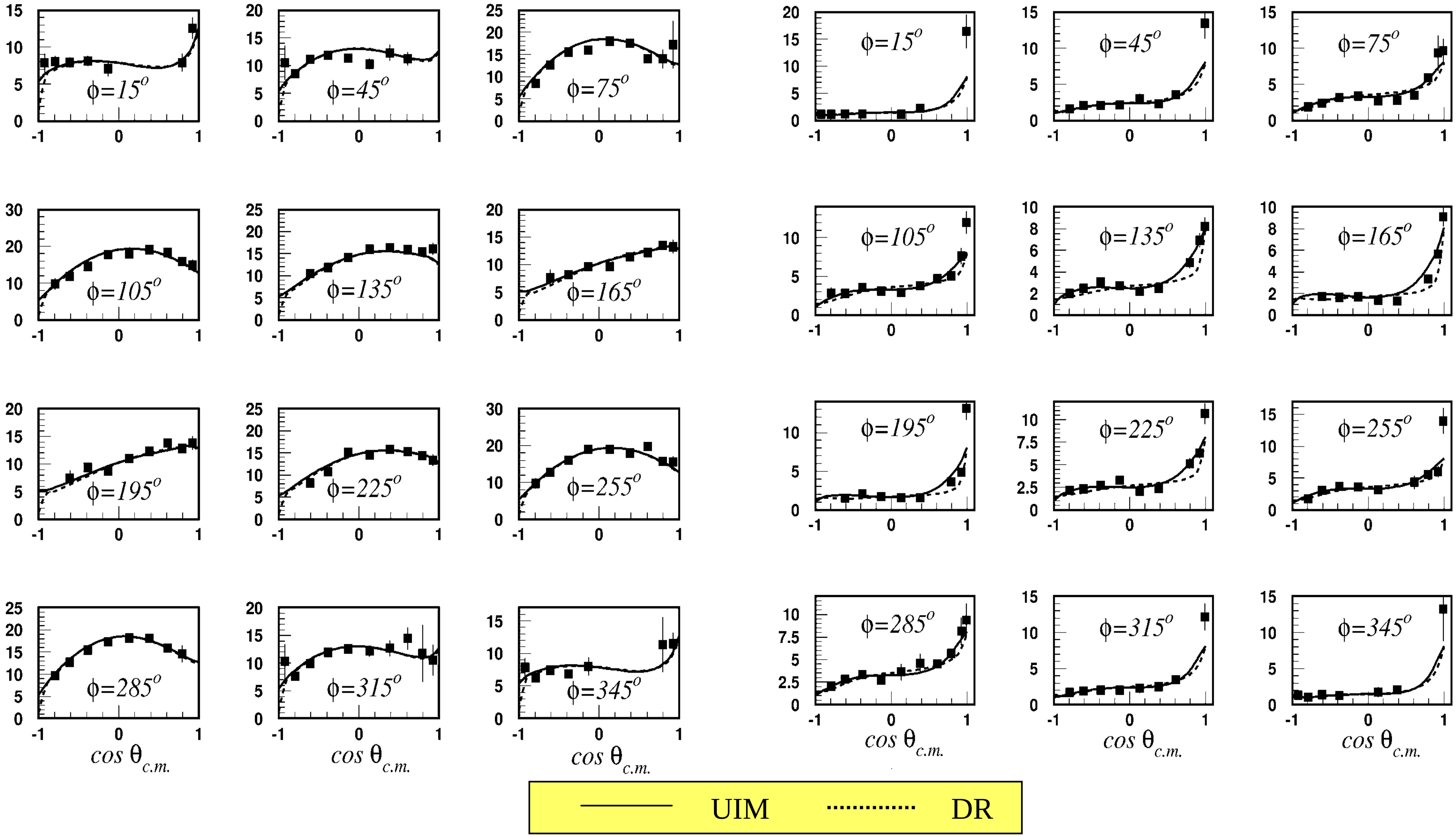
CLAS ep $\longrightarrow$ enπ^+ Unitary Isobar fit



Fit to π, η Electroproduction $\sigma_T+\varepsilon\sigma_L$, σ_{TT}, σ_{LT}

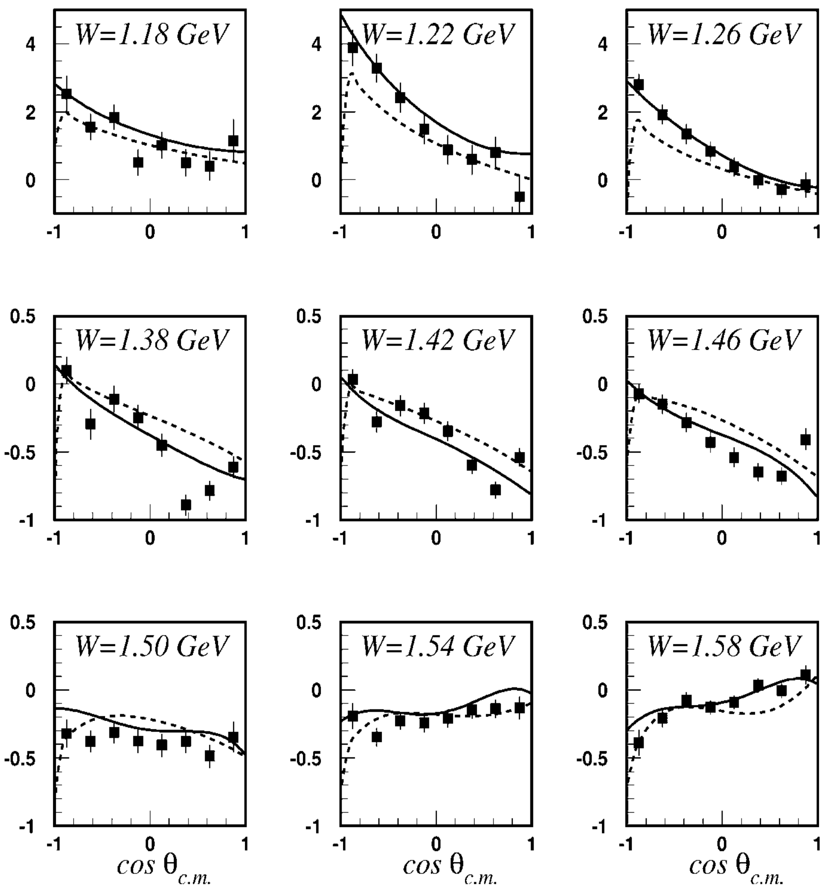
π^+

W = 1.23 GeV, Q^2=0.4 GeV^2 W = 1.53 GeV



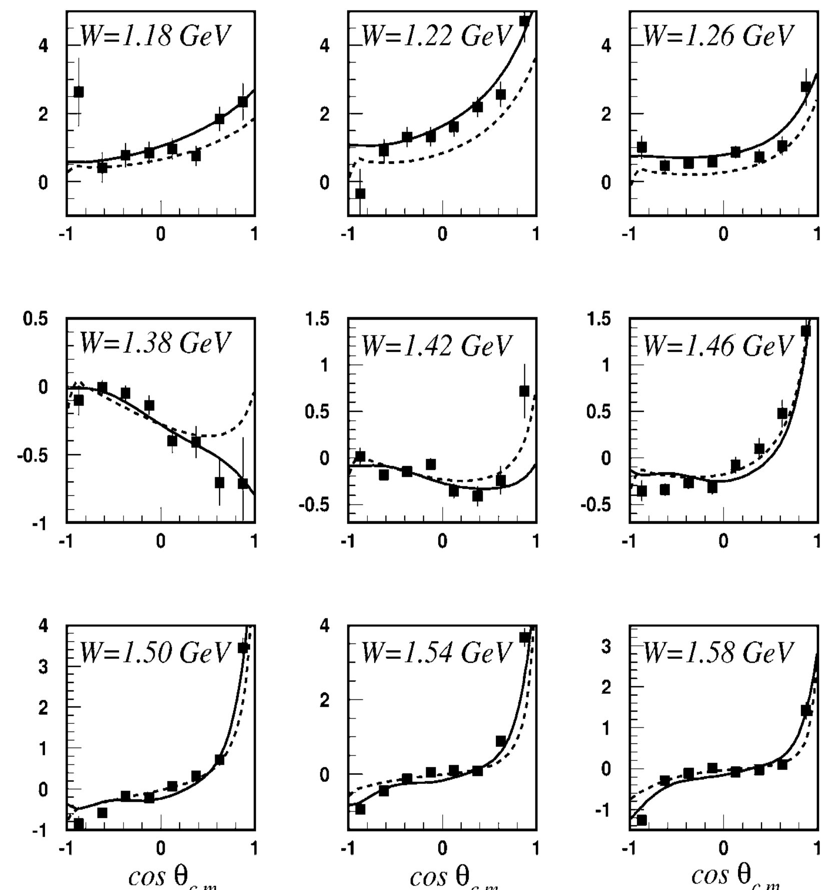
Fit to π, η Electroproduction $\sigma_{LT'}$ (Σ)

π^o W = 1.18 – 1.58 GeV



$\sigma_{LTP}(\pi^o)$

π^+ W = 1.18 - 1.58 GeV



$\sigma_{LTP}(\pi^+)$

UIM DR

Global Fit to η Photoproduction σ_T, Σ

η W > 1.49 GeV

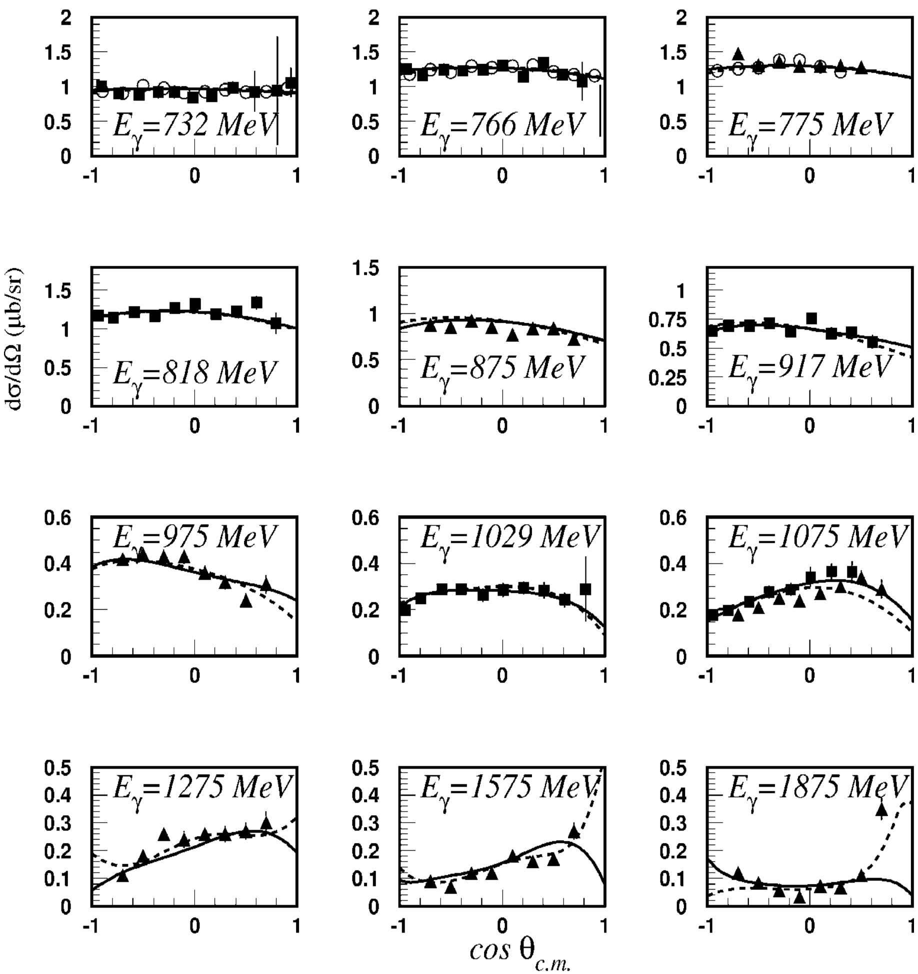


Fig. 1

η W > 1.49 GeV

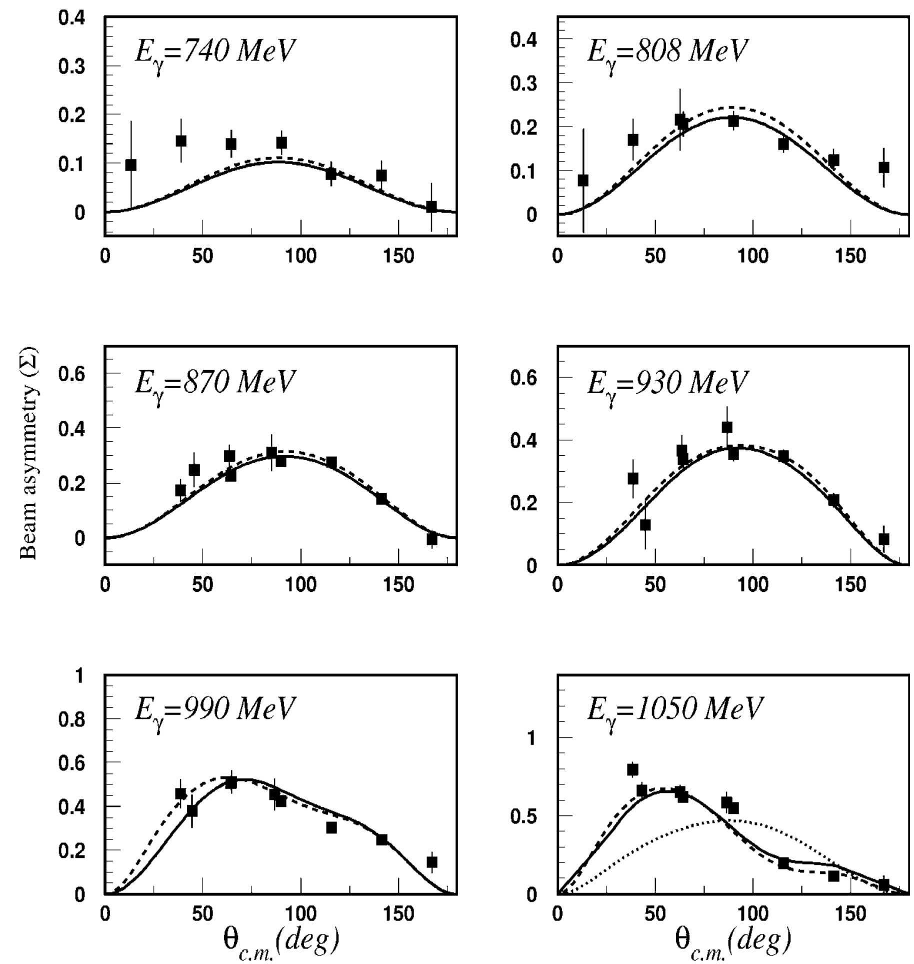


Fig. 2

UIM DR

Global Fit to η Photoproduction Target asymmetry

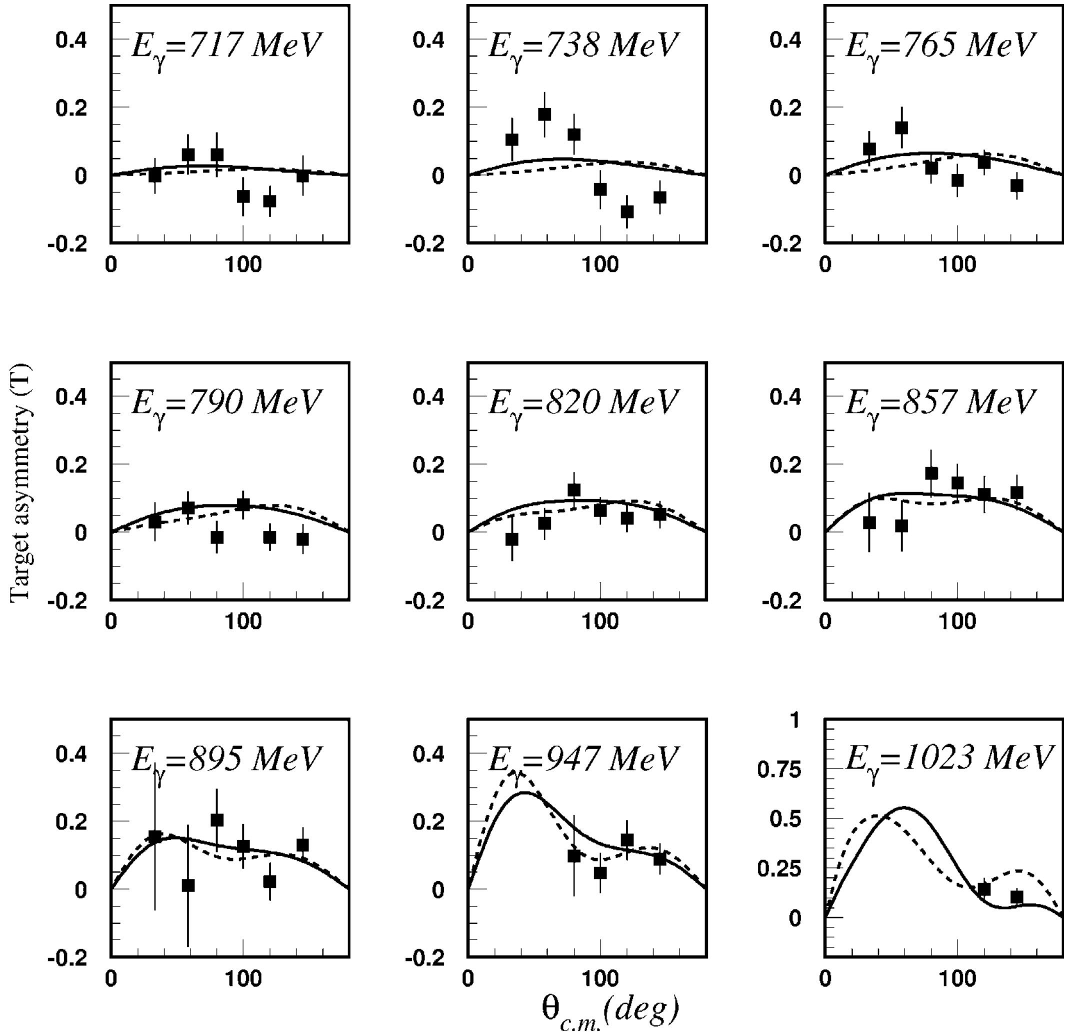
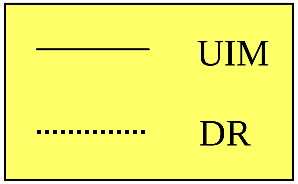
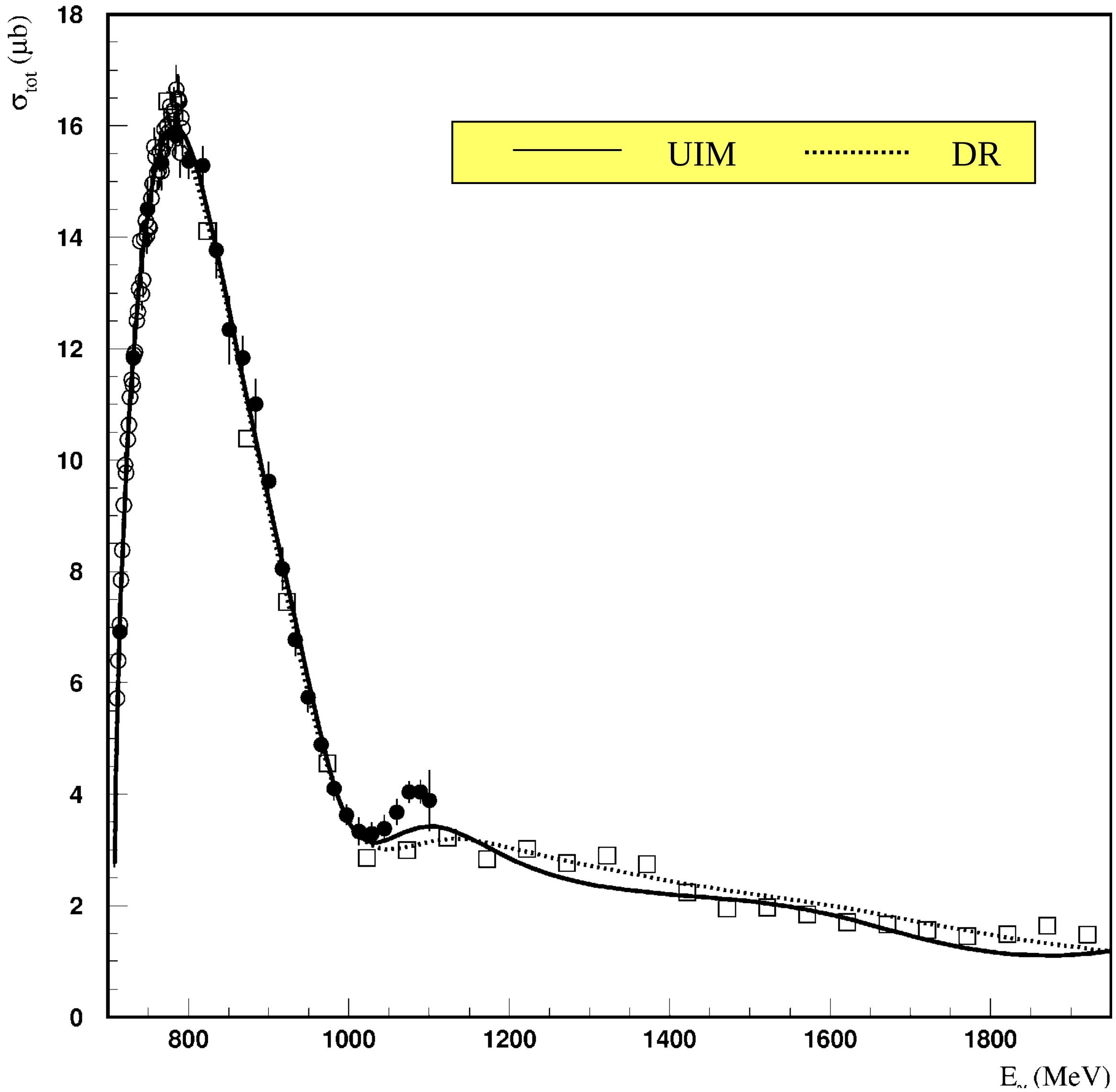


Fig. 3

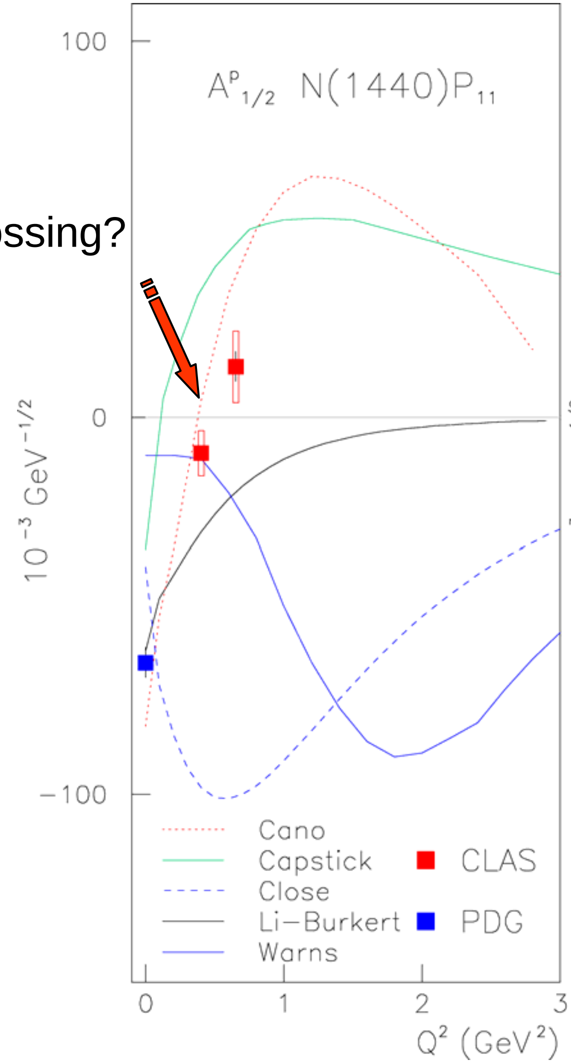


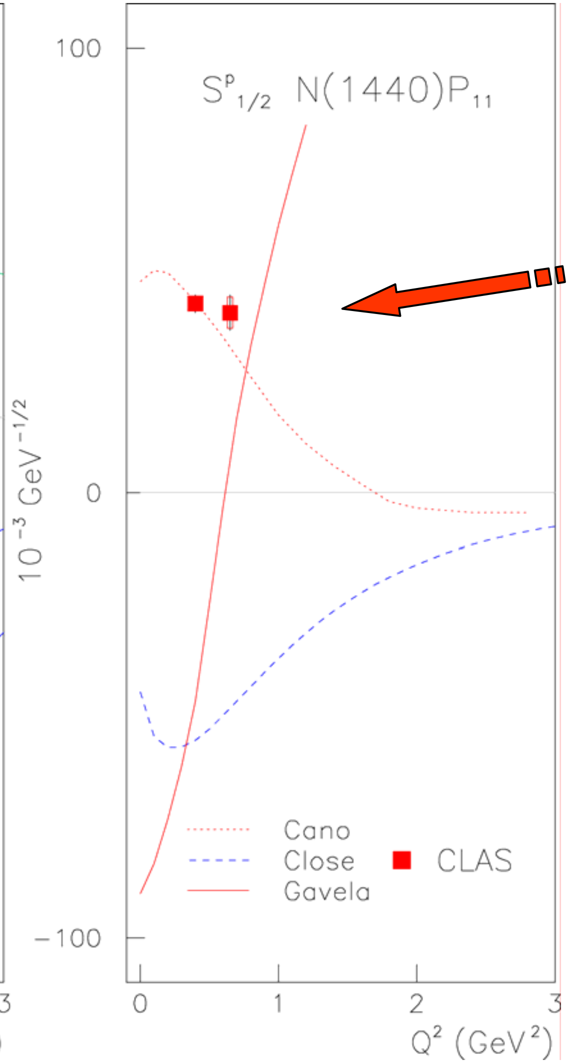
Global Fit to η Photoproduction σ_{tot}



First Results from JLab Global Analysis

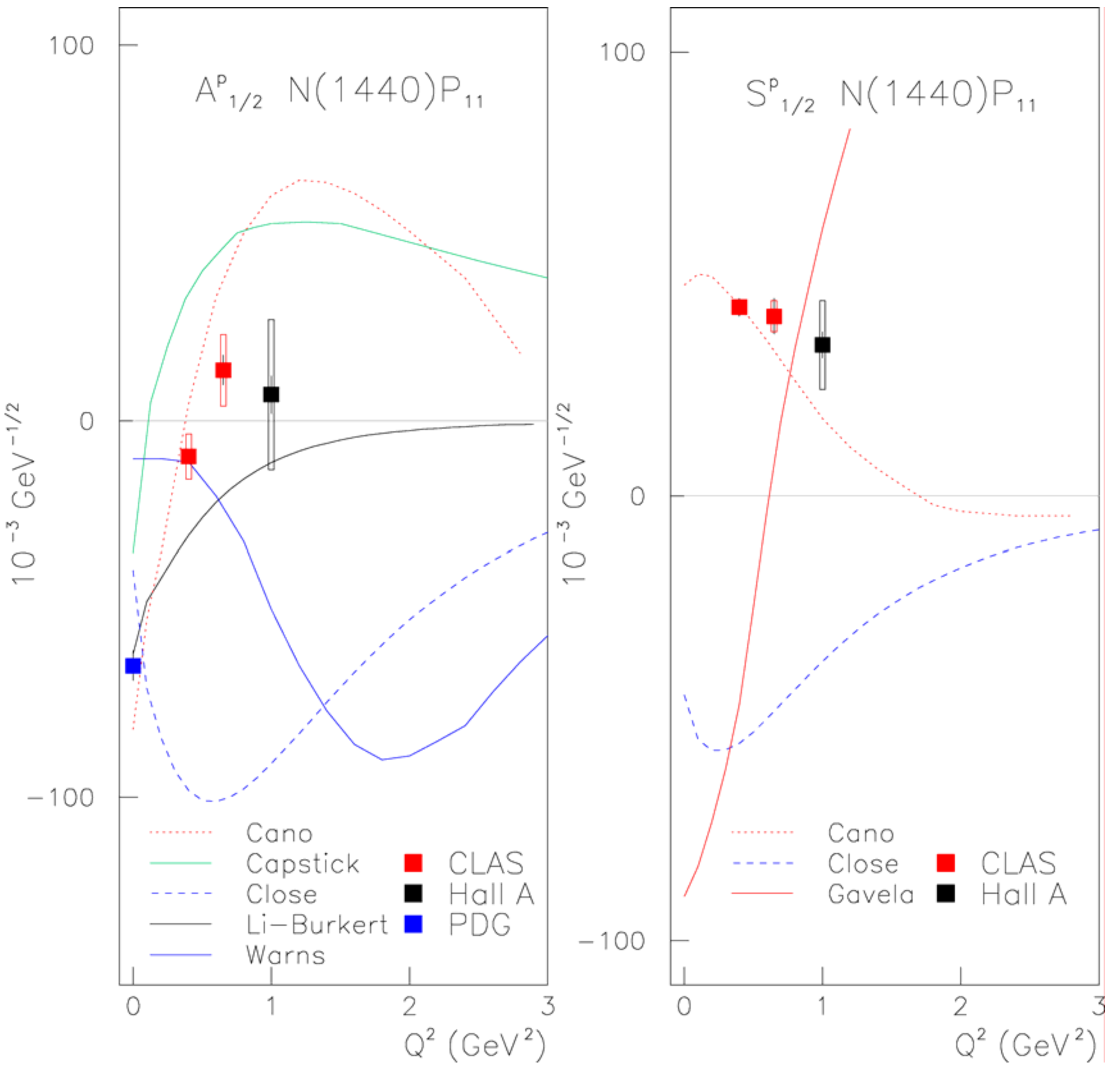
Zero crossing?



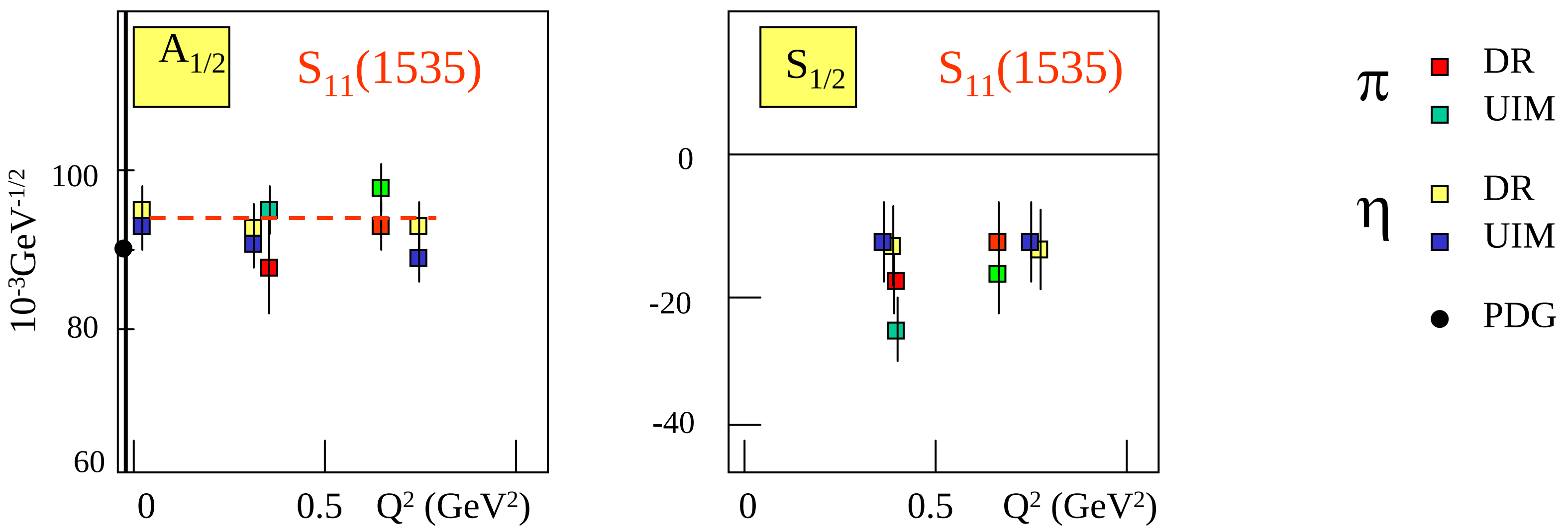


Large longitudinal coupling !

First Results from JLab Global Analysis

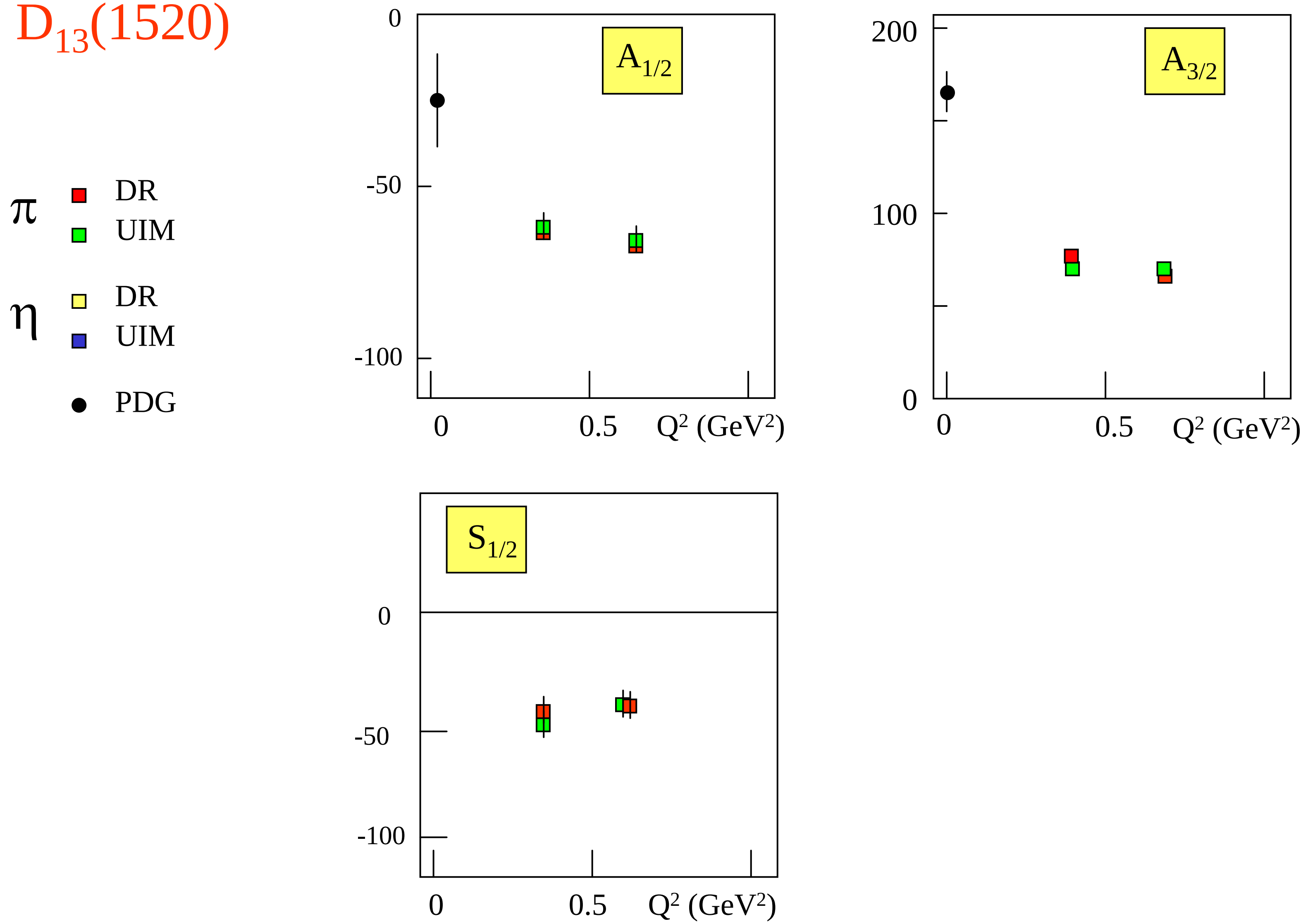


First Results from JLab Global Analysis – cont'd



First Results from JLab Global Analysis – cont'd

$D_{13}(1520)$



Third Nucleon Resonance Region

- Resonances: $S_{31}(1620)$, $S_{11}(1650)$, $D_{13}(1700)$, $D_{15}(1675)$, $F_{15}(1680)$, $P_{11}(1710)$, $P_{13}(1720)$, $D_{33}(1700)$, …..

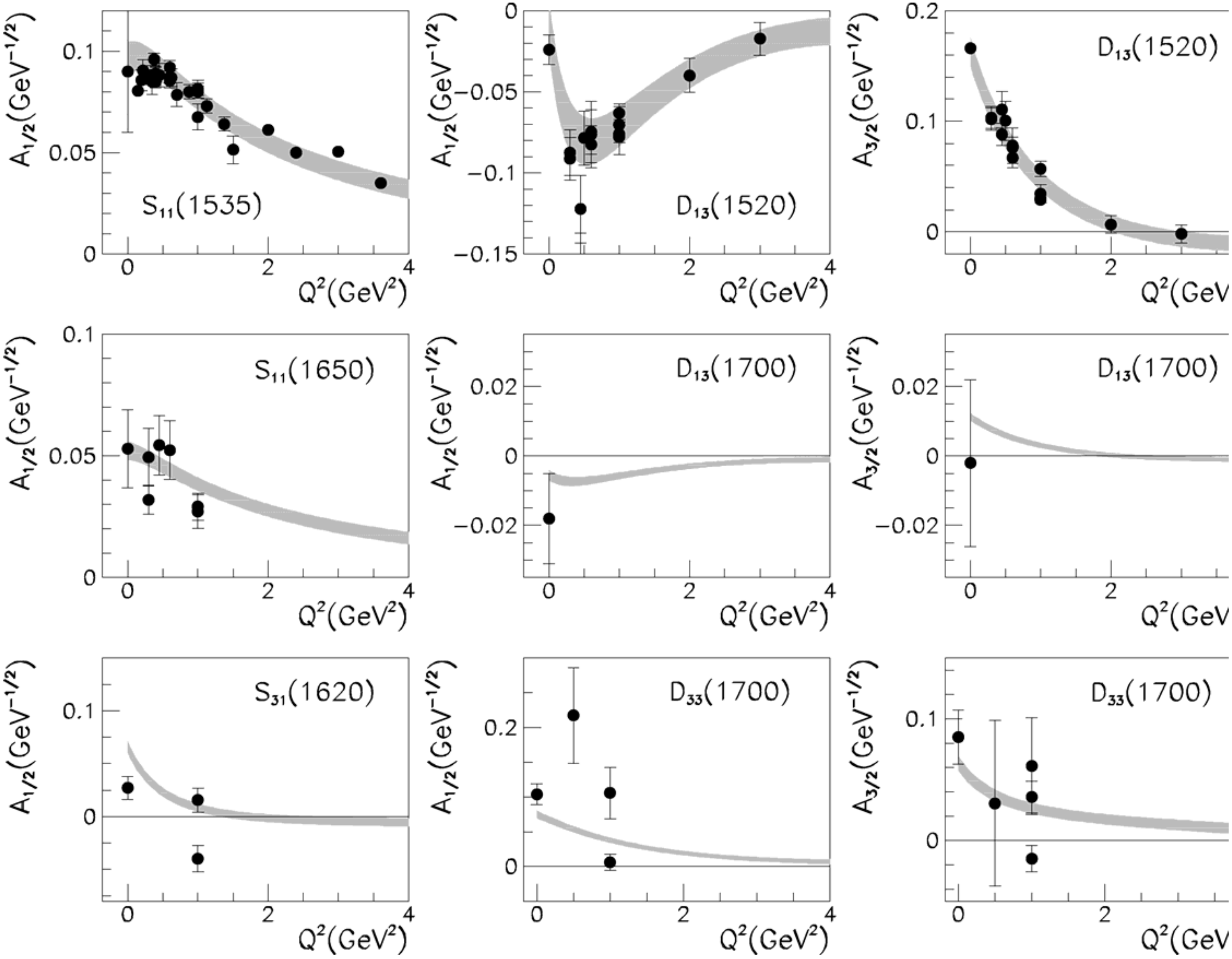
- Transition form factors in a large Q^2 range
  - test of the Single Quark Transition Model (SQTM)
    for $\gamma + [56,0^+] \longrightarrow [70,1^-]$, and
    $\gamma + [56,0^+] \longrightarrow [56,2^+]$ transitions

- Does the $P_{11}(1710)$ have a 5-quark component as required by the chiral soliton model of Diakonov et al.? χSM predicted the $\Theta^+(1540)$ as a 5-quark state.

- Main tools to study transitions in 3rd resonance region
  - $\gamma^* N \longrightarrow N\pi$
  - $\gamma^* N \longrightarrow N\pi\pi$, many states couple strongly to $N\pi\pi$

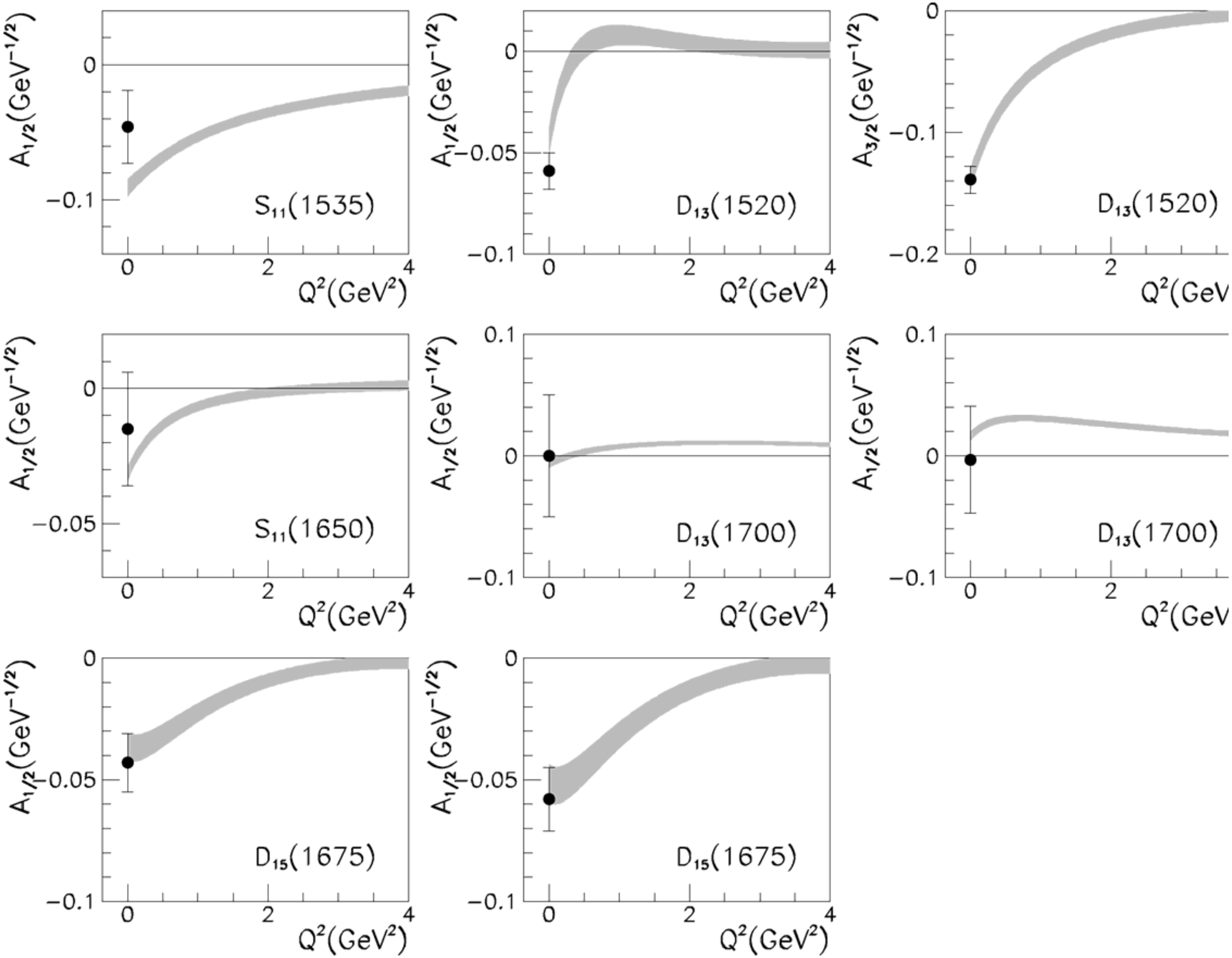
Test of the Single Quark Transition Model

Proton



Test of the Single Quark Transition Model

Neutron



Tools to search for “Missing” Resonances

- Search for new baryon states (N*, Δ) in $N\pi\pi$

  - Developed Isobar Model for the analysis of $p\pi^+\pi^-$ photo- and electro-production data (Moscow-JLab-Genova).

  - Developing IM including neutral channel, e.g. $n\pi^+\pi^o$, $p\pi^o\pi^o$.

  - Developed event-based PWA approach for the analysis of $p\pi^+\pi^-$ photo-production data.

- Search for new baryon states (N*, Δ) in KY.

  - Appropriate tools for resonance analysis are currently lacking. Coupled-channel analysis essential because of large background.

- Search for new baryon states (N*) in $p\omega$.

  - Dynamical Model developed by Y. Oh. We are adopting this model to fit experimental data in single channel analysis. Need to include other channels because of background.

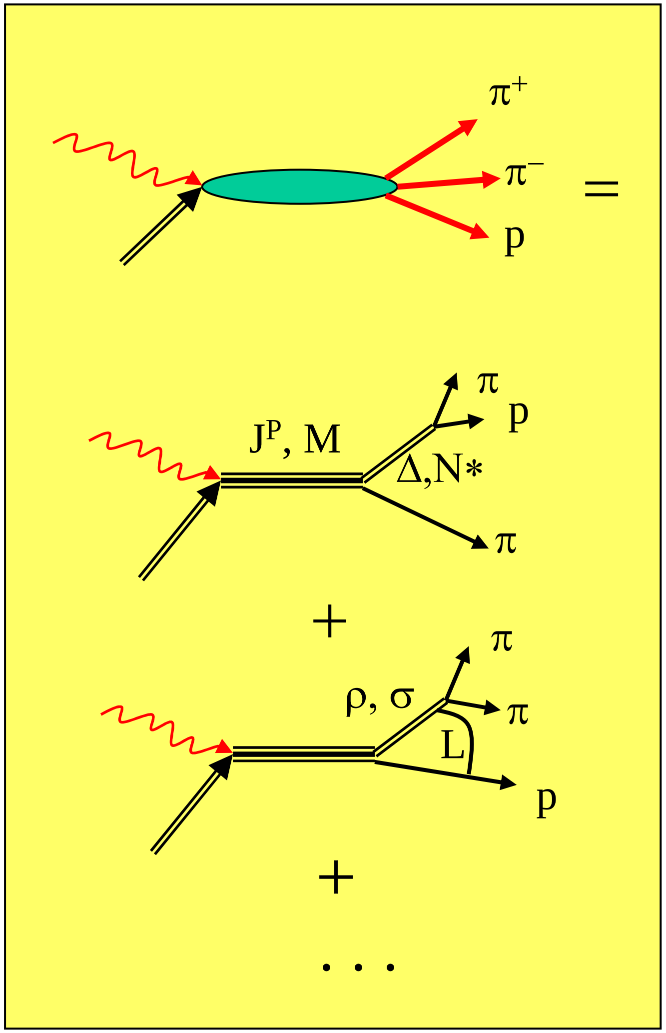
Partial Wave Formalism for $\gamma p \longrightarrow p\pi^+\pi^-$

- Transition matrix:

$$T_{fi} = \langle p\pi^+\pi^-;\tau_f|T|\gamma p;E\rangle$$
$$= \sum_\alpha \langle p\pi^+\pi^-;\tau_f|\alpha\rangle\langle\alpha|T|\gamma p;E\rangle$$
$$= \sum_\alpha \psi^\alpha(\tau_f)V^\alpha(E)$$

- Decay amplitude $\psi^\alpha(\tau_f)$ calculated using isobar model:
  e.g. $J^P, M = ½^+, +½ \longrightarrow [\Delta^{++}\pi^-]_{l=1}, \lambda_{Pf} = +½$

- Production amplitude $V^\alpha(E)$ is fitted in unbinned maximum likelihood procedure. Assume $V^\alpha(E)$ is independent of E in small energy range.

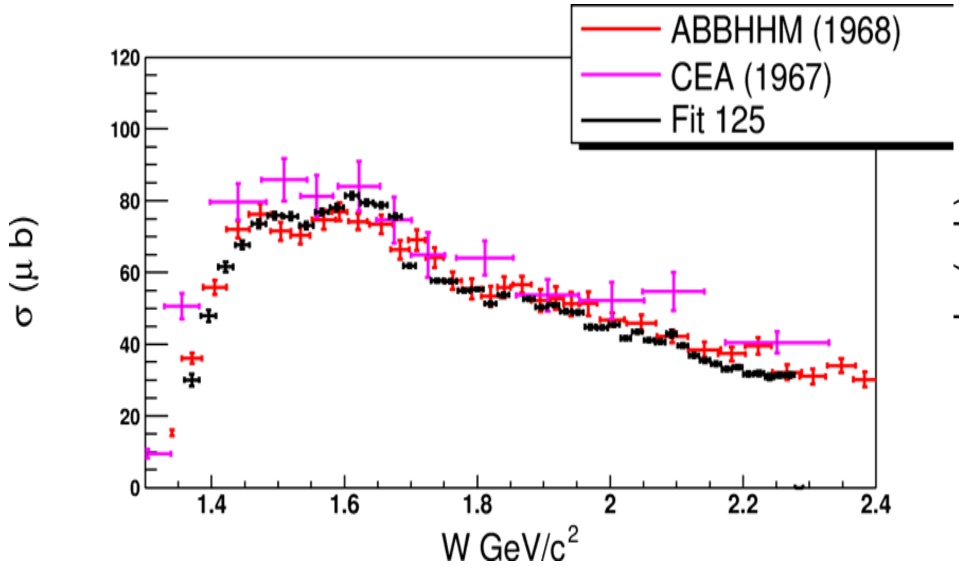


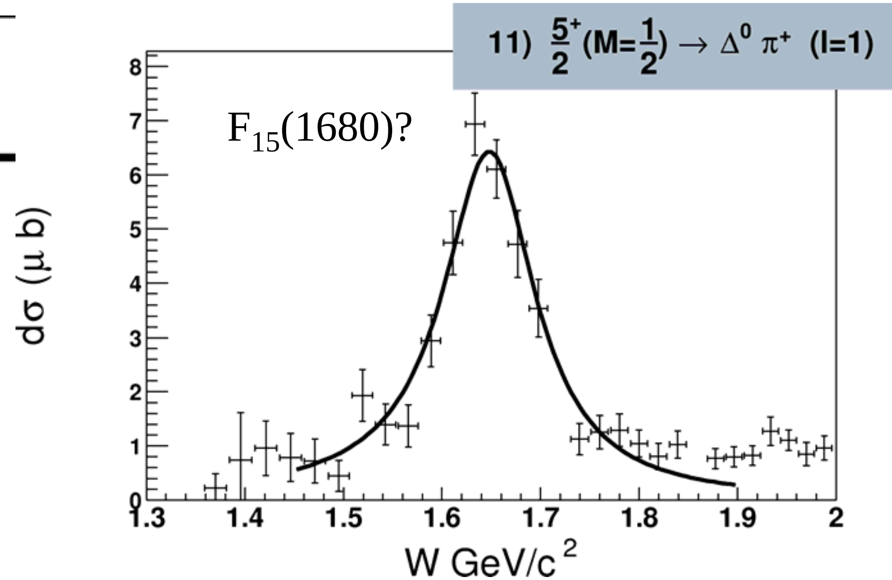
Waves in the current analysis

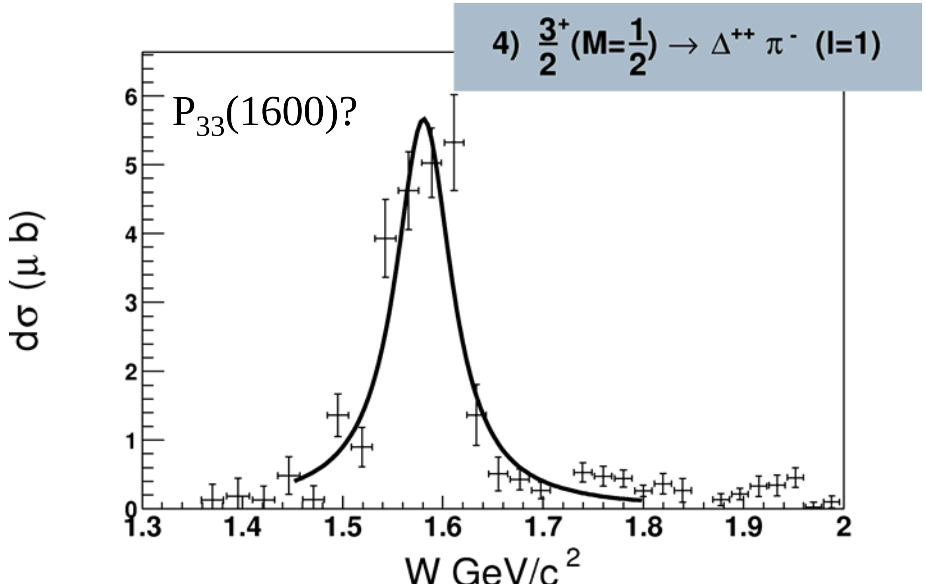
J^P	M	Isobars
$1/2^+$	1/2	$\Delta\pi$ (=$\{\Delta^{++}\pi^-, \Delta^o\pi^+\}$)
$1/2^-$	1/2	$\Delta\pi$, $(p\rho)_{(s=1/2}$
$3/2^+$	1/2, 3/2	$(\Delta\pi)_{(l=1)}$,$(p\rho)_{(s=1/2)}$,$(p\rho)_{(s=3/2;l=1,3)}$,$N^*(1440)\pi$
$3/2^-$	1/2, 3/2	$(\Delta\pi)_{(l=0,2)}$
$5/2^+$	1/2, 3/2	$(\Delta\pi)_{(l=1)}$, $p\sigma$
$5/2^-$	1/2, 3/2	$(\Delta\pi)_{(l=2)}$

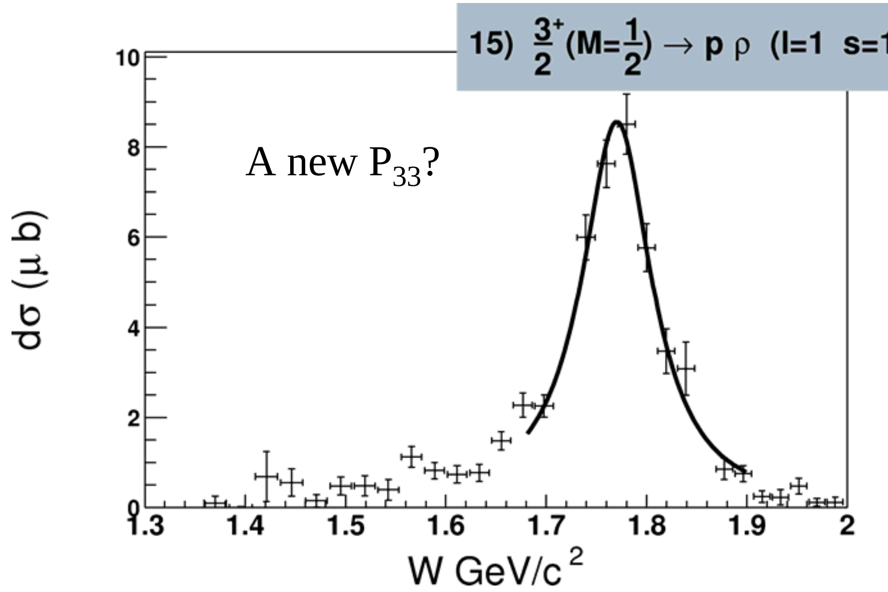
- Total of 35 waves (complex amplitudes)
- Diffractive production ("t-channel") also included

Samples of event-based PWA for $\gamma p \rightarrow p\pi^+\pi^-$



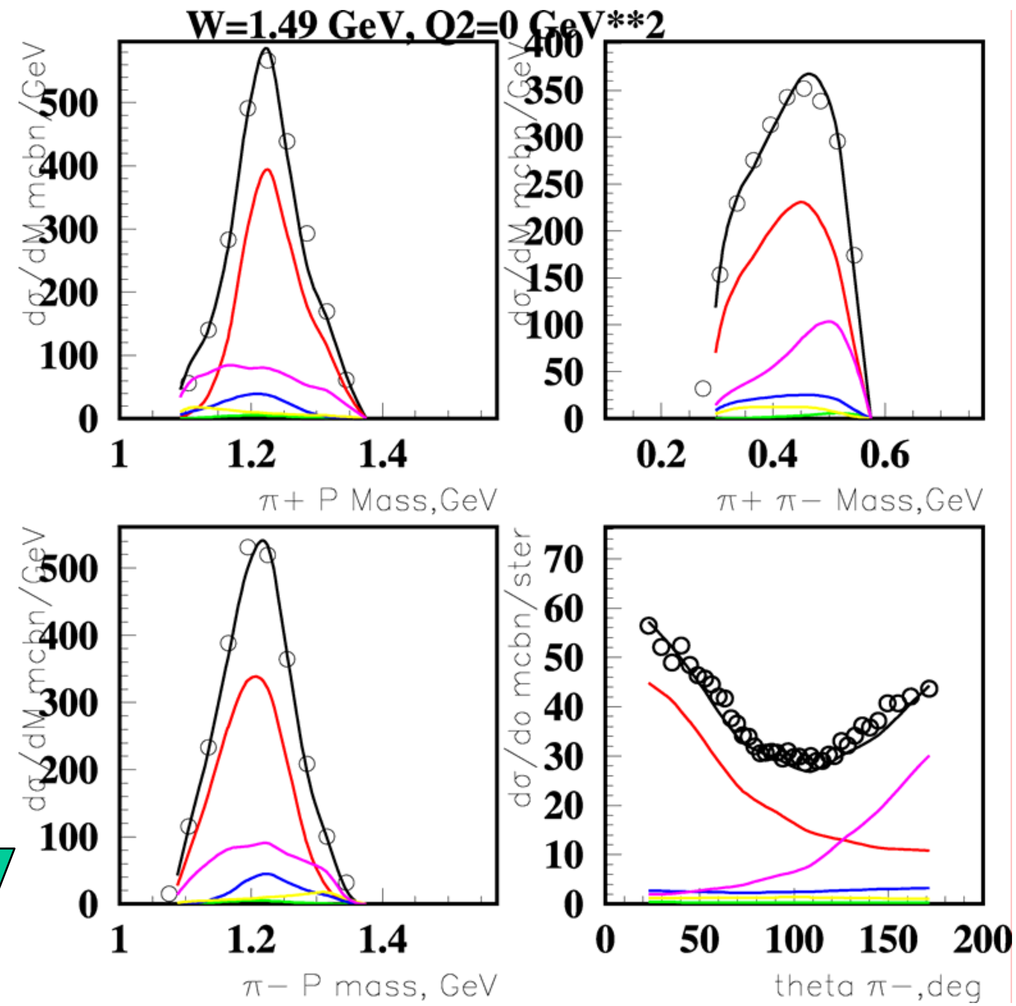






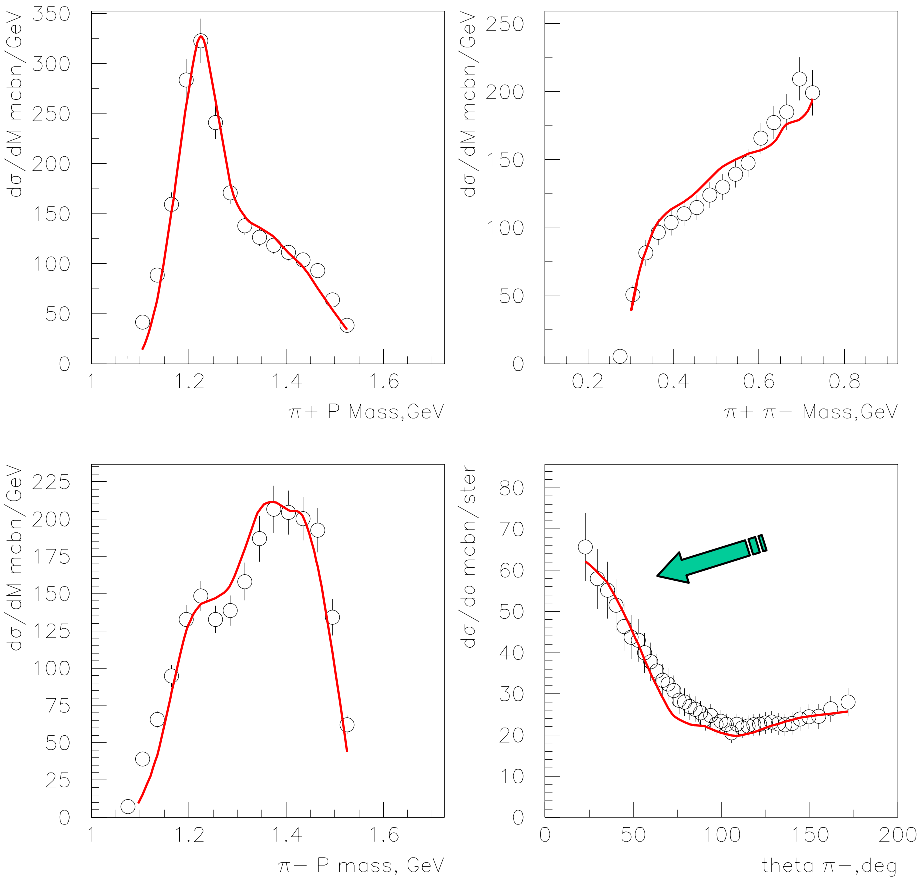
Isobar Model for the $\gamma^* N \longrightarrow N\pi\pi$ channel

- All established resonances included as Breit-Wigners
- Non-resonant Born terms for all $\Delta(1232)\pi$ isospin channels, and for $D_{13}(1520)\pi$ channels.
- Non-resonant $p\rho^o$ production through diffractive ansatz.
- High mass behavior through Reggeon exchange.
- Good fits to one-dimensional cross sections at low $p\pi^+\pi^-$ masses.

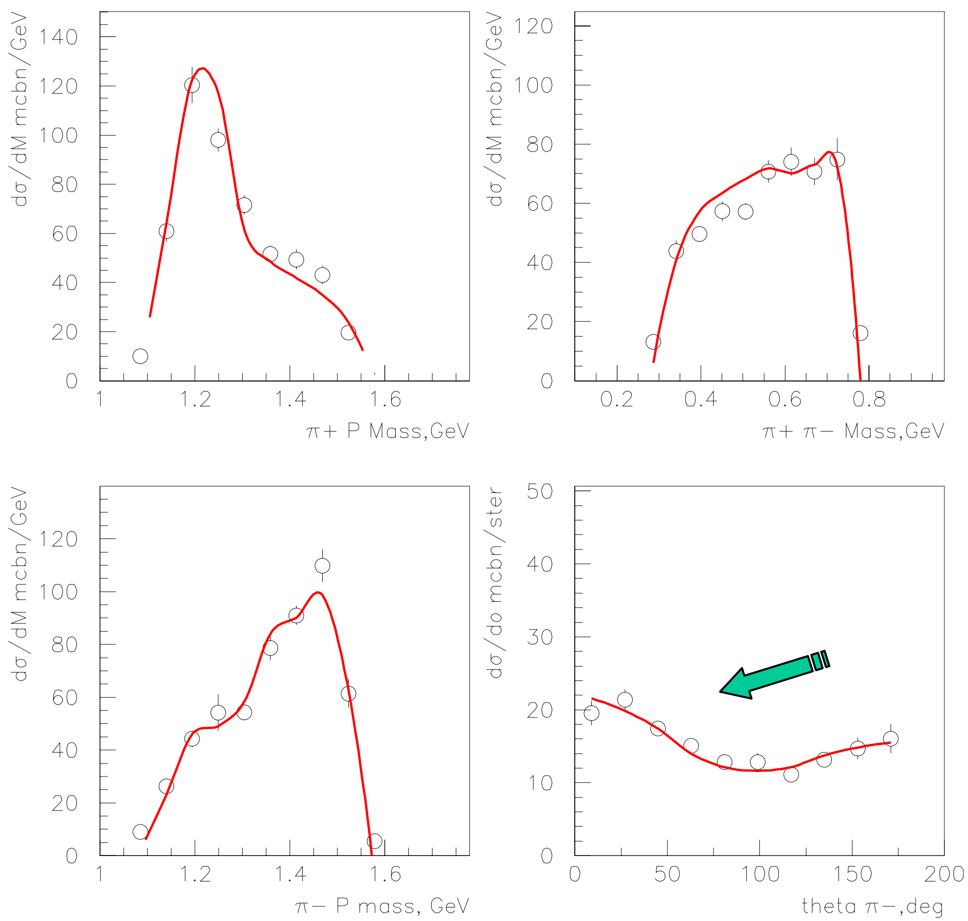


Isobar Model for the $\gamma^*N \longrightarrow N\pi\pi$ channel

W=1.70 GeV Q^2=0.

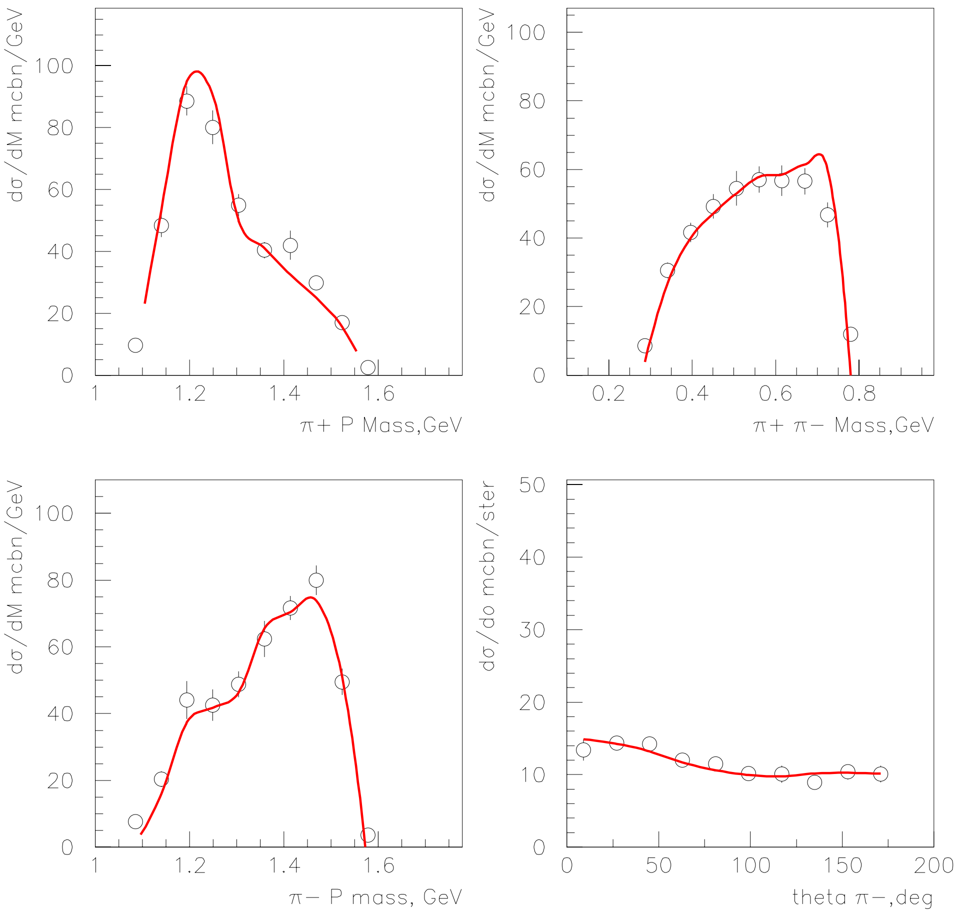


W=1.71 GeV Q^2=0.65 GeV^2

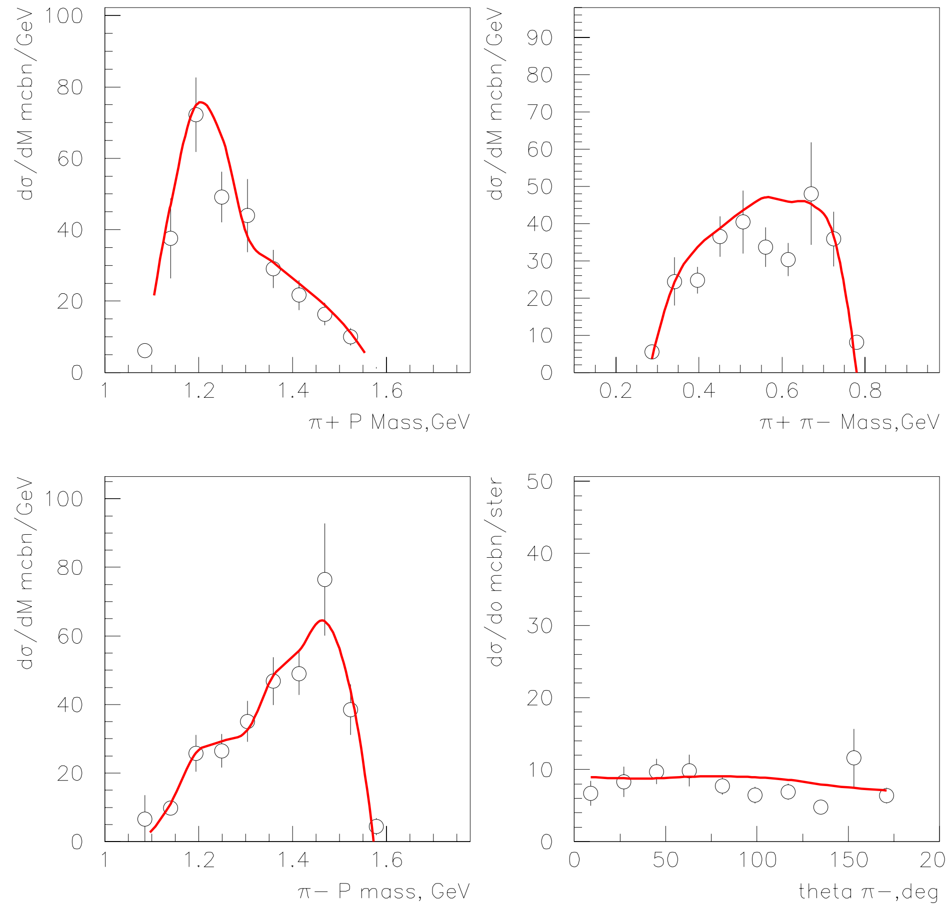


Isobar Model for the $\gamma^{*}N \longrightarrow N\pi\pi$ channel

W=1.71GeV Q^2=0.95 GeV^2



W=1.71 GeV Q^2=1.30 GeV^2



Resonances in $\gamma^* p \longrightarrow p\pi^+\pi^-$

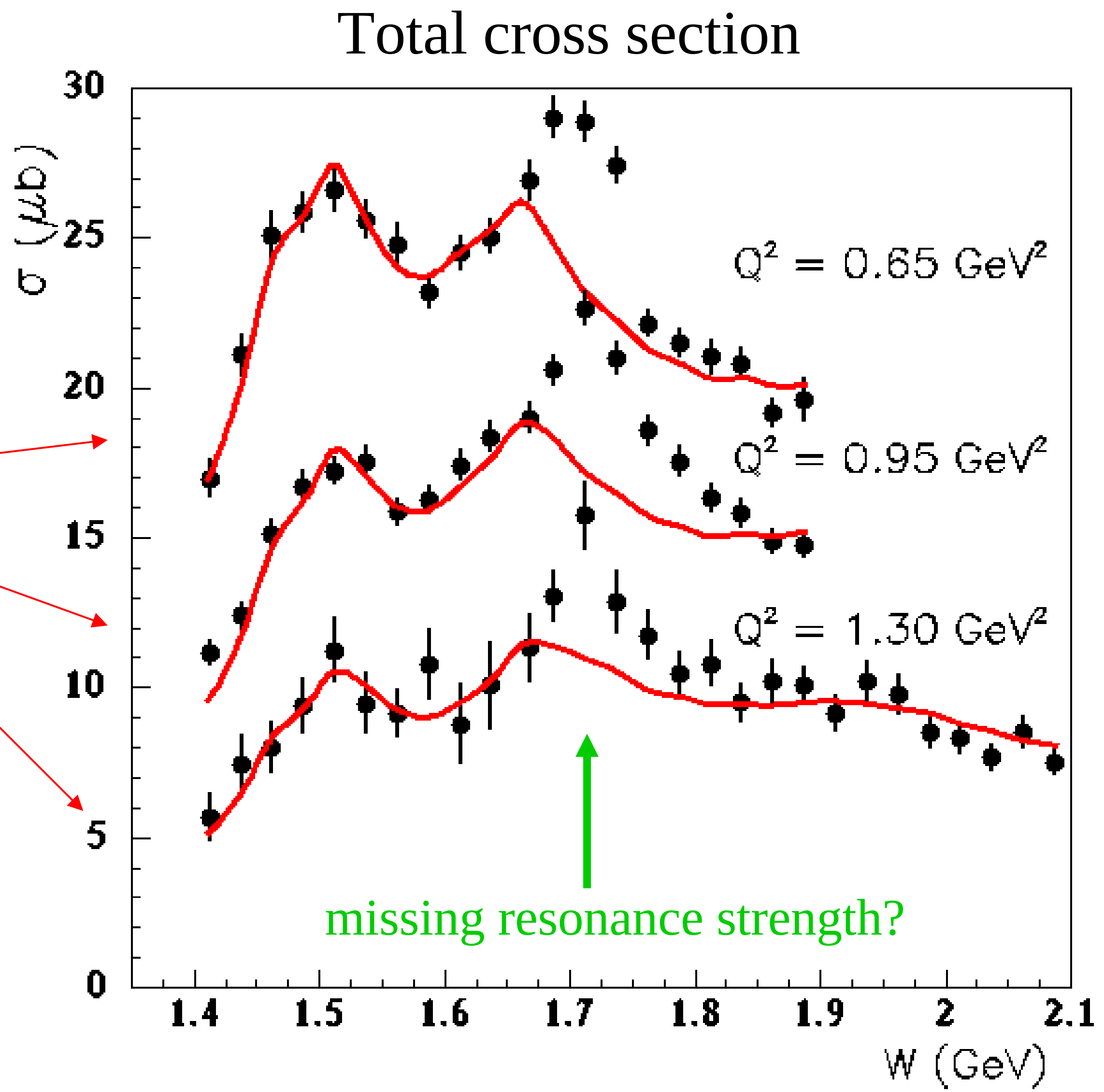
CLAS

Genova-Moscow Isobar model fit

$\Gamma_{N\pi\pi}$ PDG

$\Gamma_{N\gamma}$ AO/SQTM

(with amplitudes adjusted)



Isobar fit to $D_{13}(1700)$ and new P_{I3}

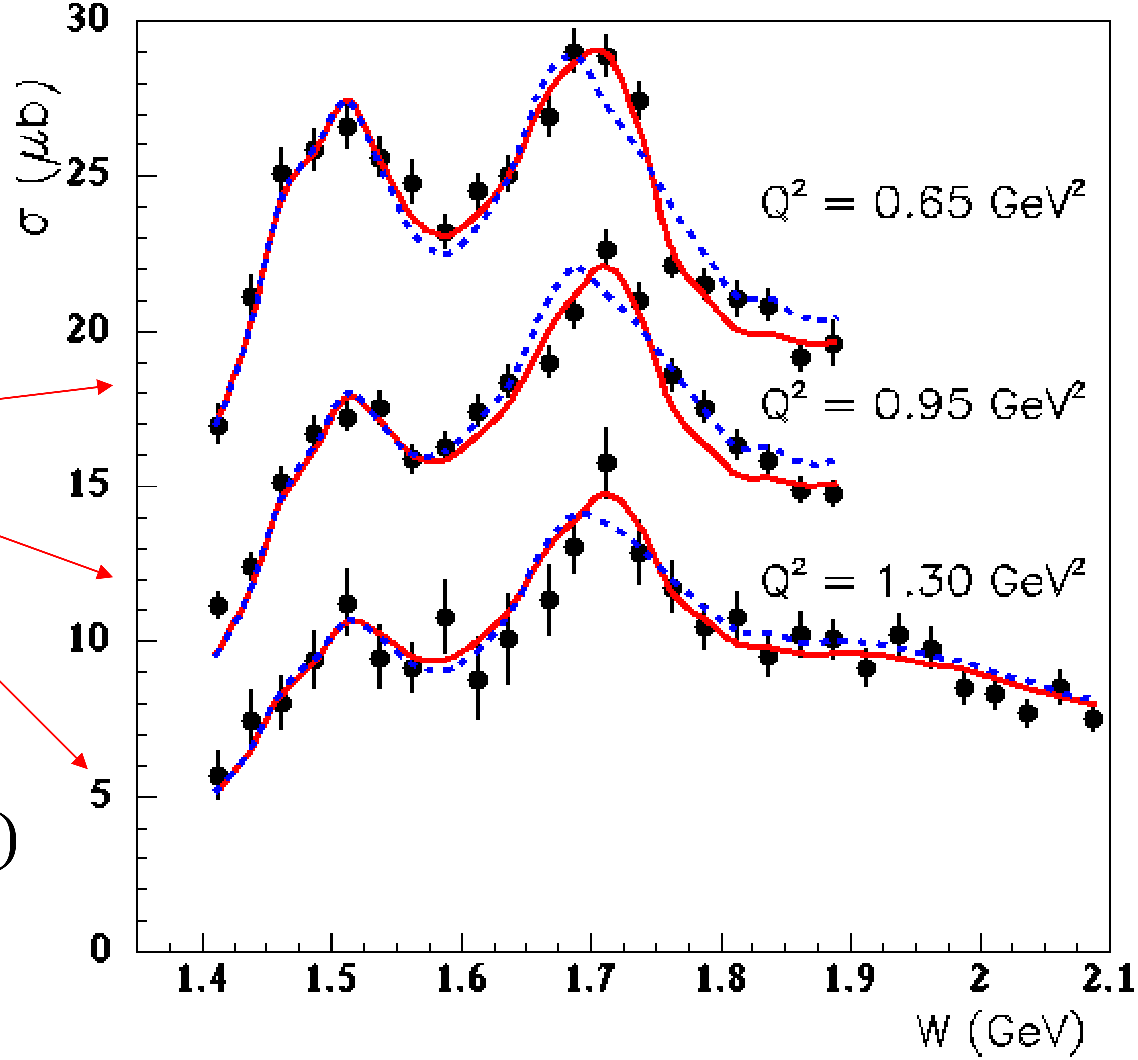
CLAS

Isobar model fit

$\Gamma_{N\pi\pi}$ PDG

$\Gamma_{N\gamma}$ AO/SQTM

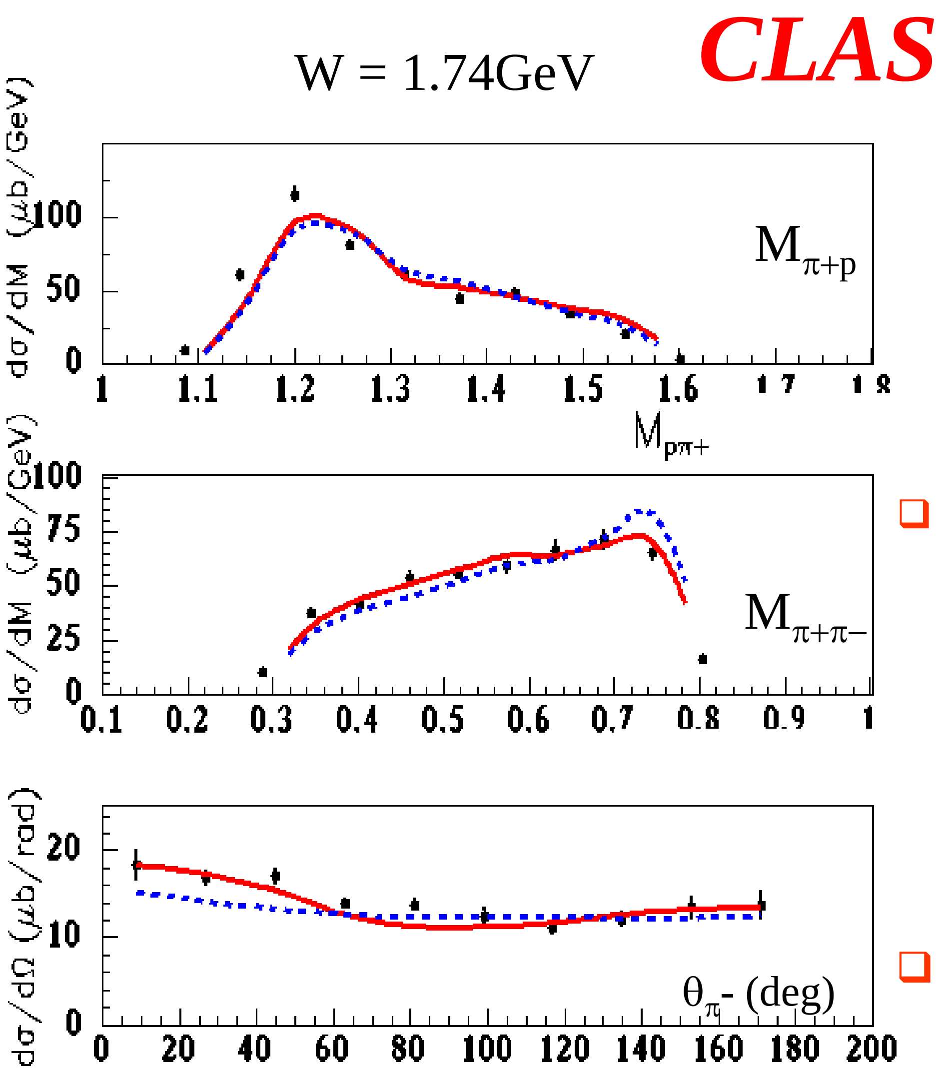
Total cross section



P_{I3}

$D_{13}(1700)$

Isobar fit - A new P_{I3} state?



- Data described best by new P_{I3}

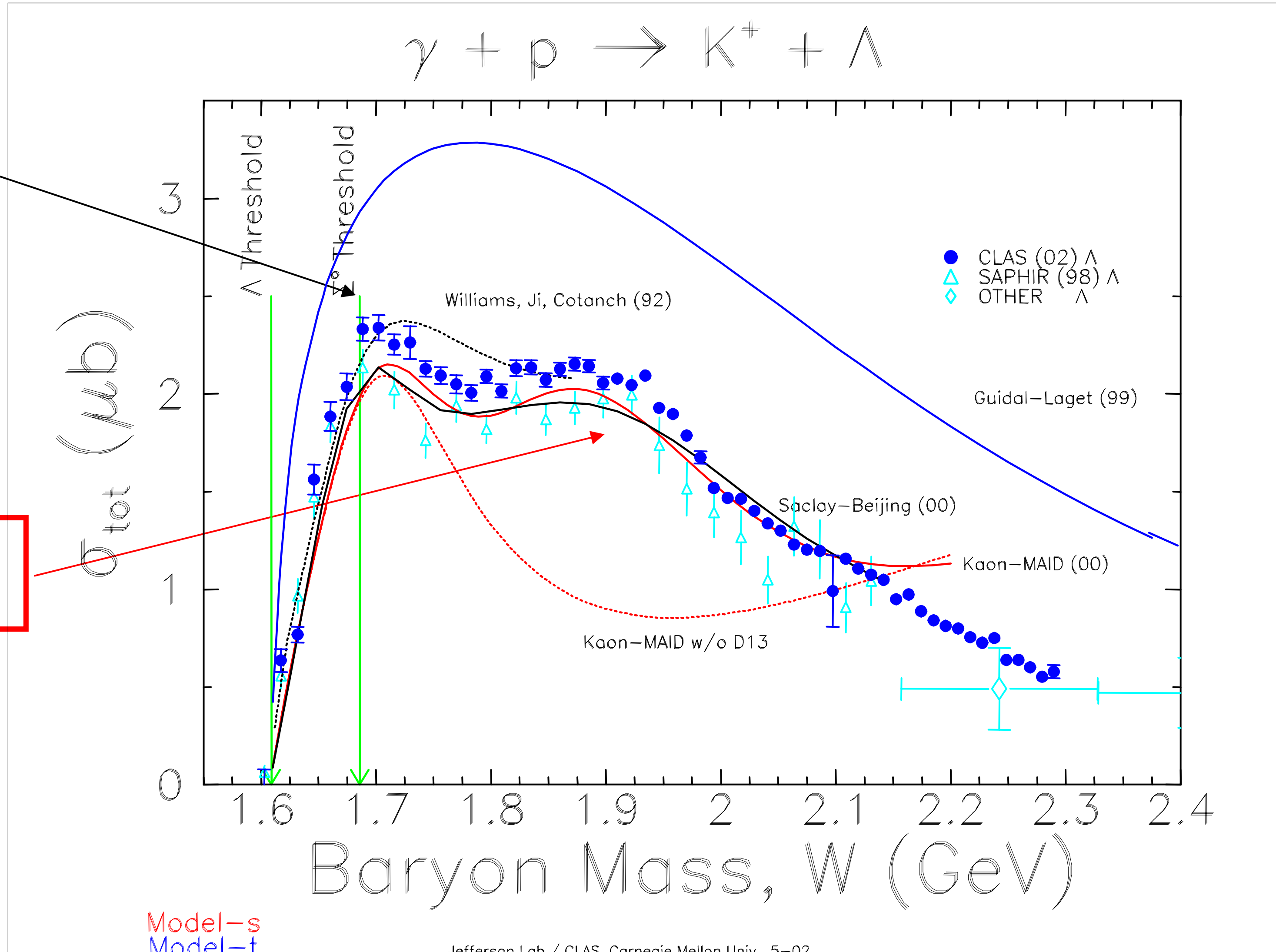
M = 1.72 +/- 0.02 GeV	1650-1750
Γ_T = 114 +/- 19 MeV	100-200
$\Delta\pi$: 0. 63+/- 0.12	~ 0
$N\rho$: 0.19 +/- 0.09	0.8 - 0.9
	known P_{13}

- consistent with "missing" P_{13} state, but mass low

Strangeness Photoproduction

Dominant resonances
$S_{11}(1650)$
$P_{11}(1710)$
$P_{13}(1720)$

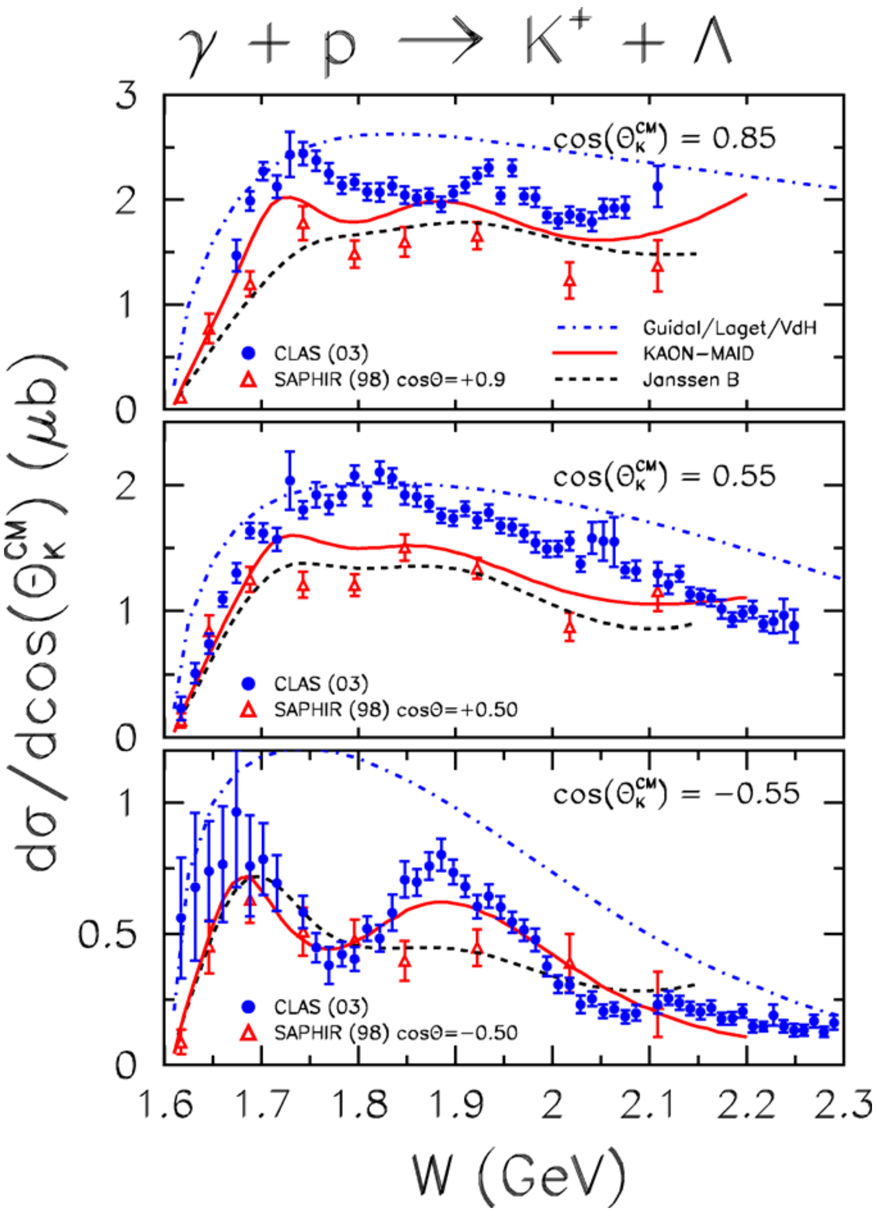
$D_{13}(1895)$?



Similar data sets exist from SAPHIR.

Carnegie Mellon

Strangeness Photoproduction



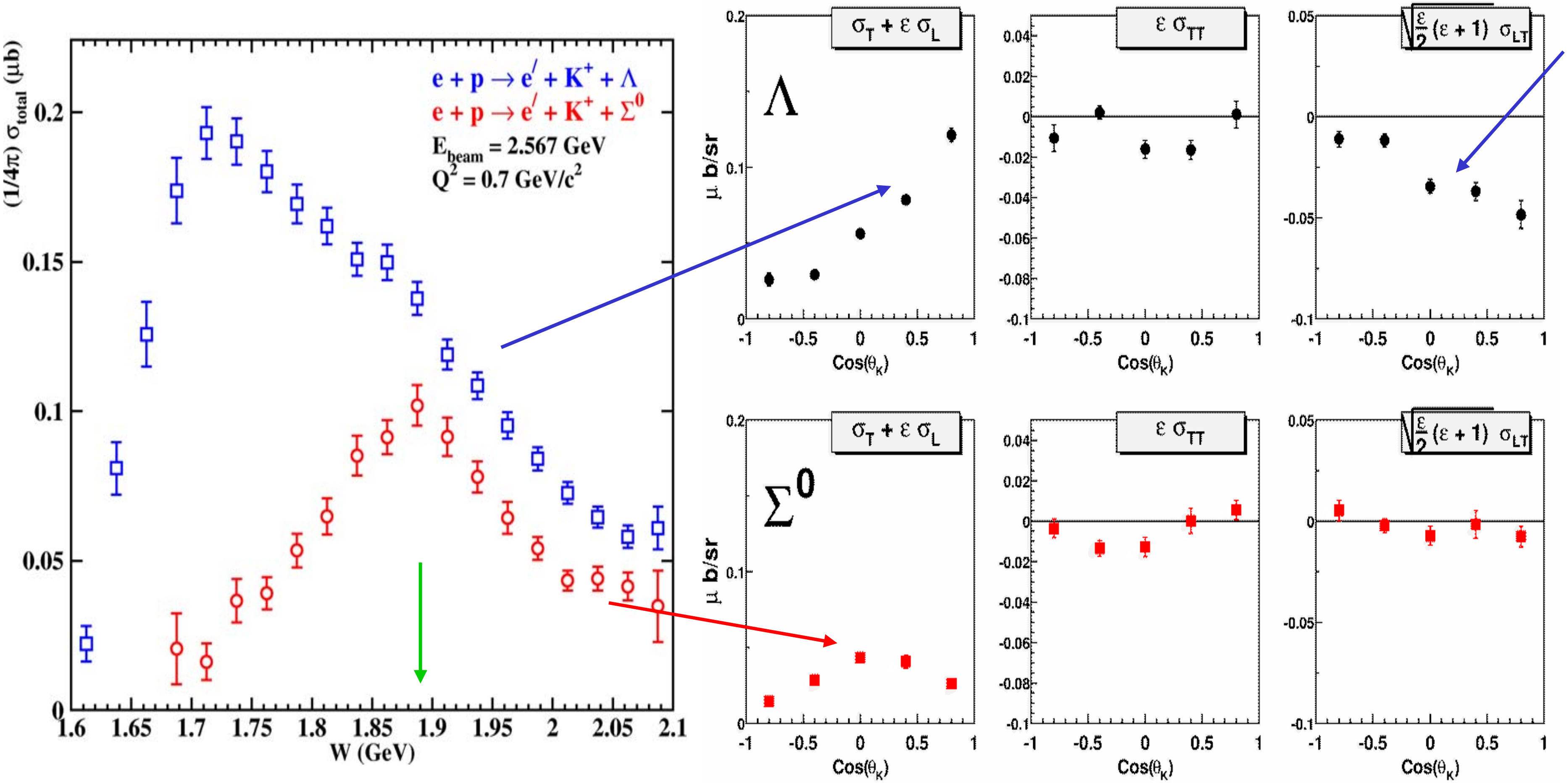
- Sample of data covering the full kinematic range in energy and angles for $K^+\Lambda$ and $K^+\Sigma$, including recoil polarization

- Data indicate significant resonance contributions, interfering with each other and with non-resonant amplitudes.

- Extraction of resonance parameters requires a large effort in partial wave analysis and reaction theory.

Strangeness in electroproduction

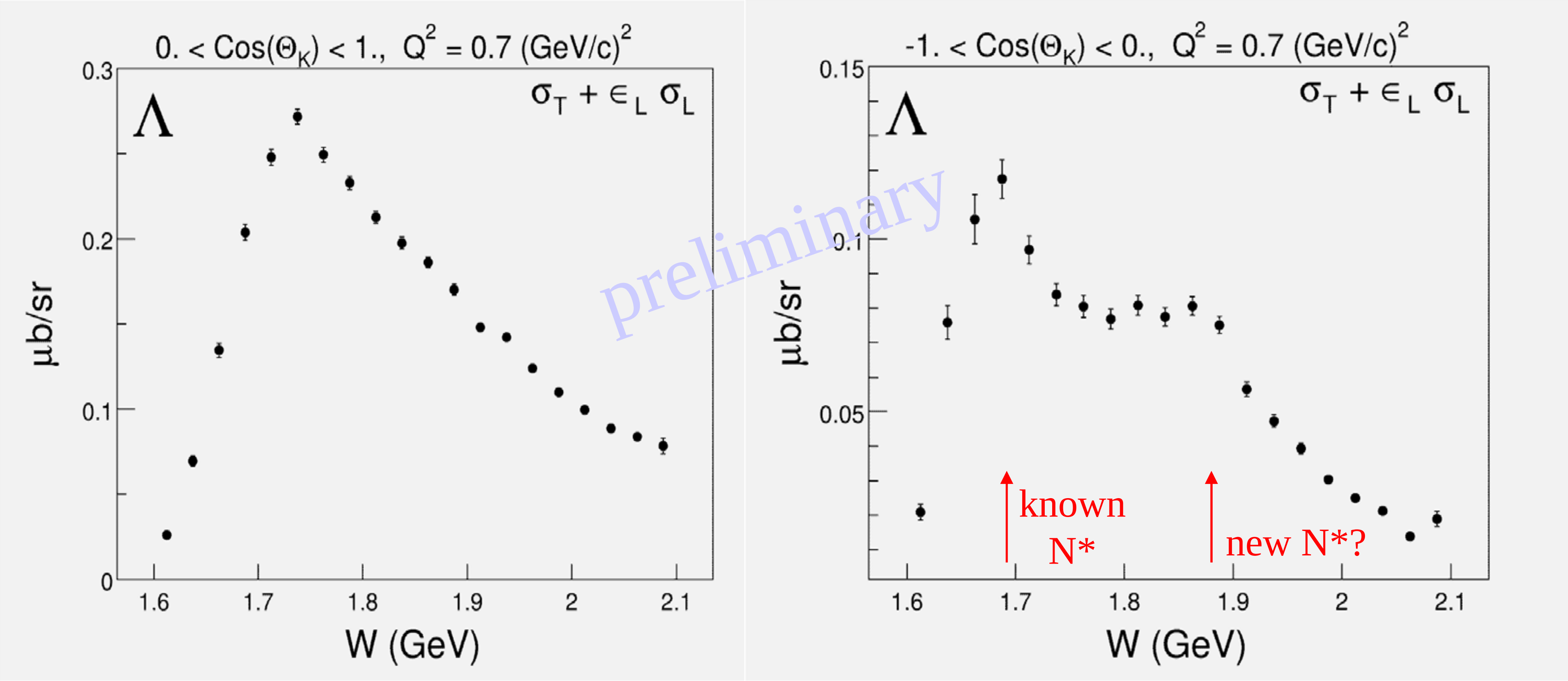
CLAS ep $\longrightarrow$ eK^+Y response functions



Strangeness in electroproduction

CLAS $\gamma^* p \longrightarrow K^+\Lambda$

forward hemisphere | backward hemishere



CLAS - Resonances in $\gamma p \longrightarrow p\omega$?

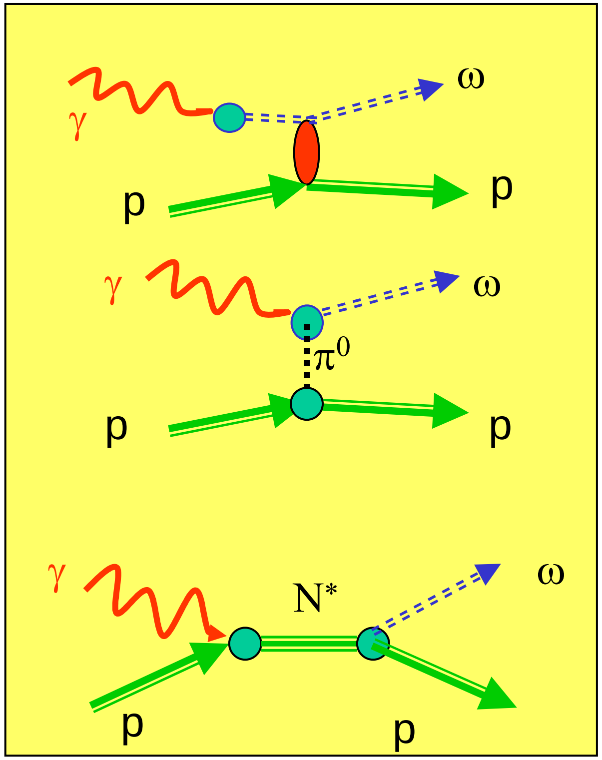
PRELIMINARY

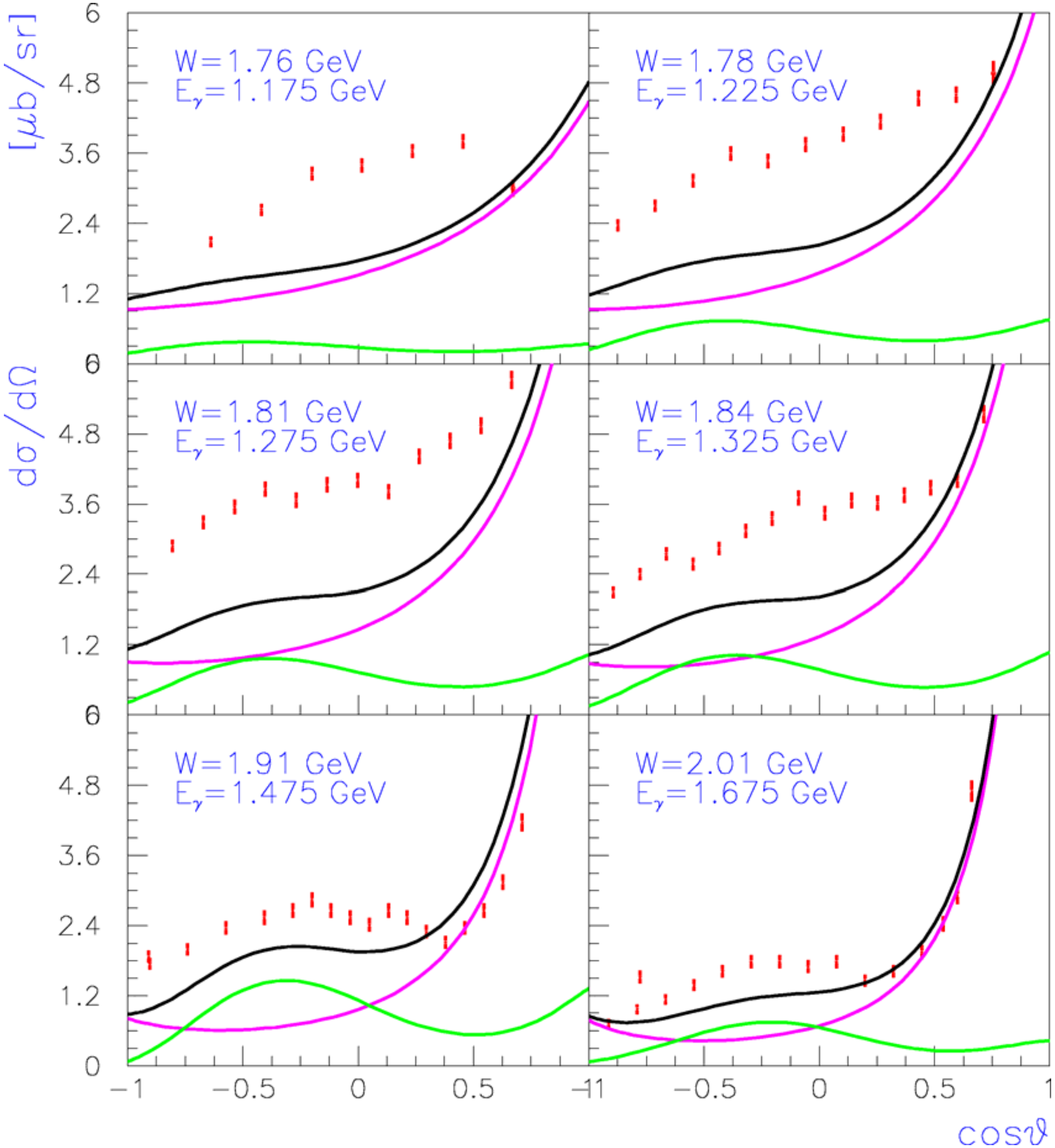
Model: Y. Oh

OPE + Pomeron

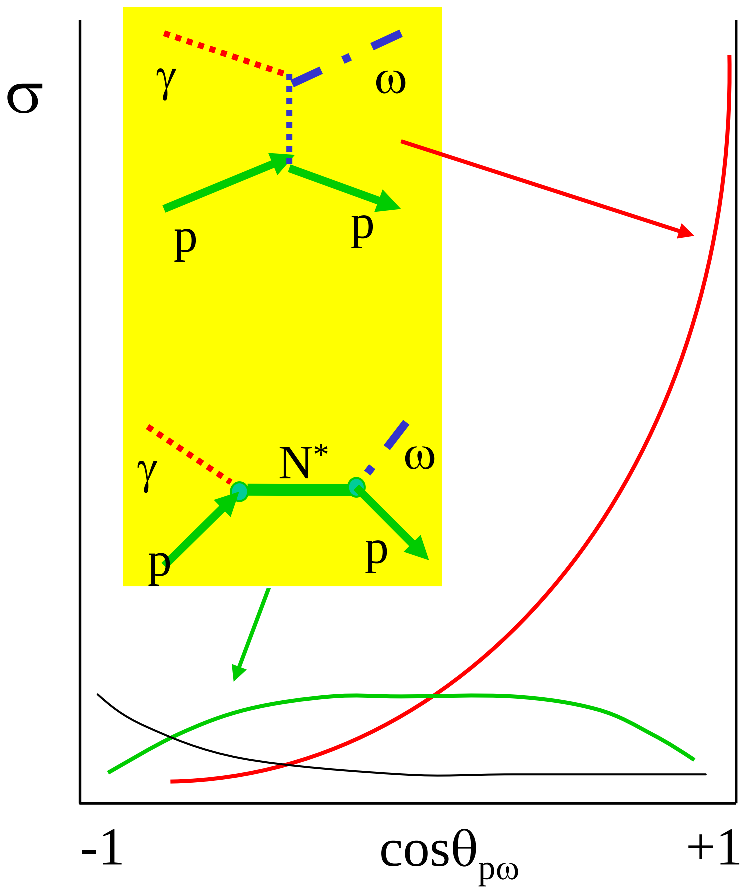
N* Capstick model

Sum

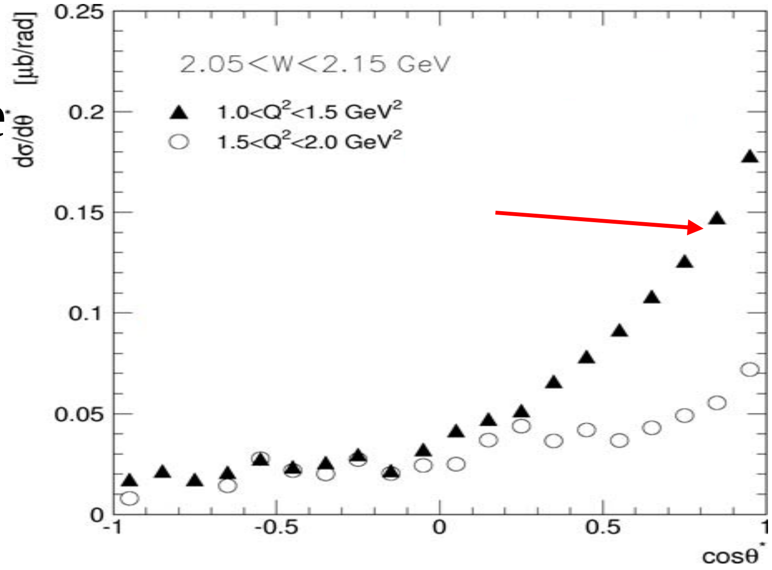




ω – electroproduction

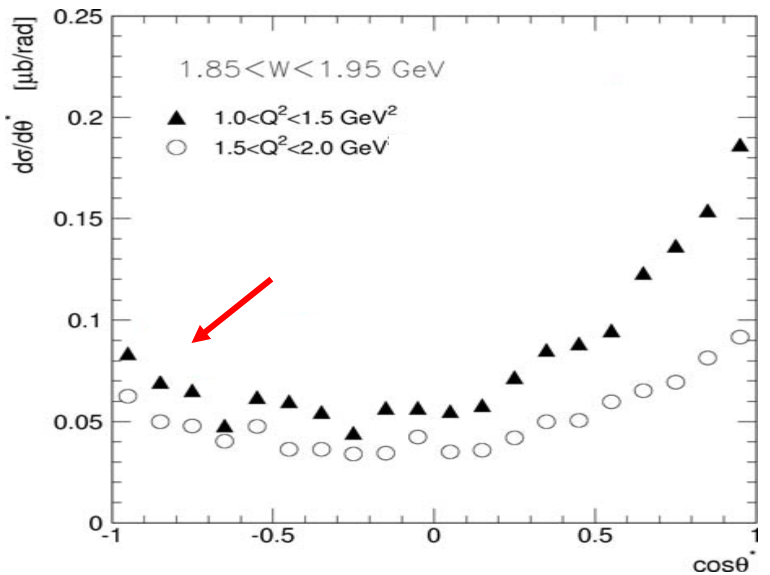


above resonance region



CLAS

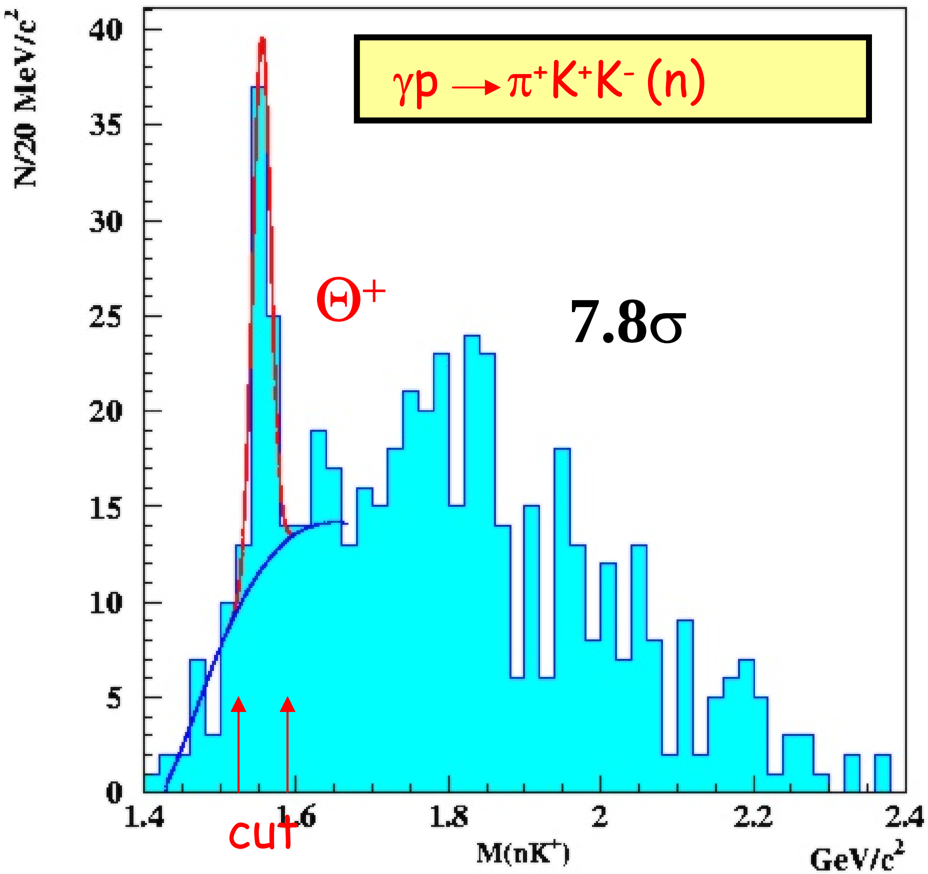
in resonance region

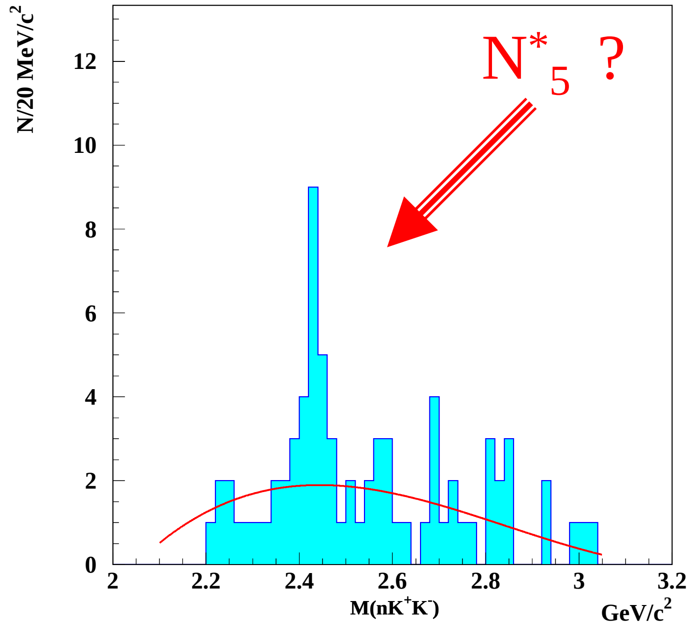


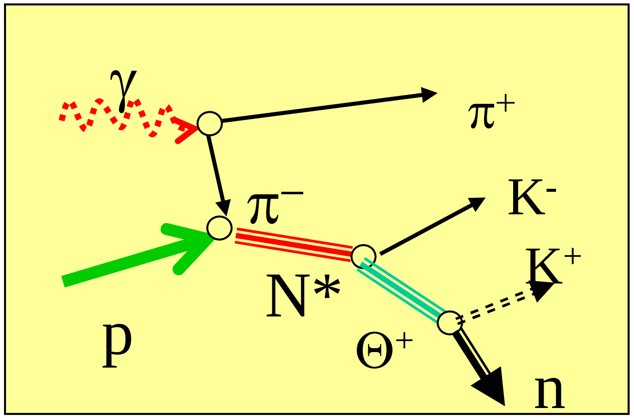
Penta-Quark Baryons

- They are part of the baryon spectrum
- Some (most?) will mix with ordinary baryons, so they have to be analyzed together with the other excited states.
- They may be produced via the decay of excited N*'s.
- They will help us to understand the symmetries underlying the baryon spectrum
- They provide fundamentally new insight into how QCD works in the complex regime where the interaction is strong

CLAS - Θ^+ Production on Protons







Combined analysis of all CLAS data on protons with > 5 GeV beam energy; minimal cuts - forward π+, backward K+.

V. Kubarovsky, *et al.; PRL submitted*

NA49 Experiment – Θ^+

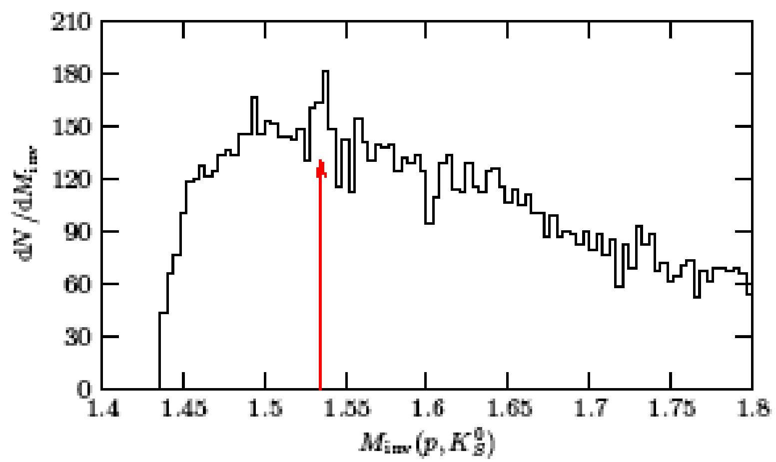
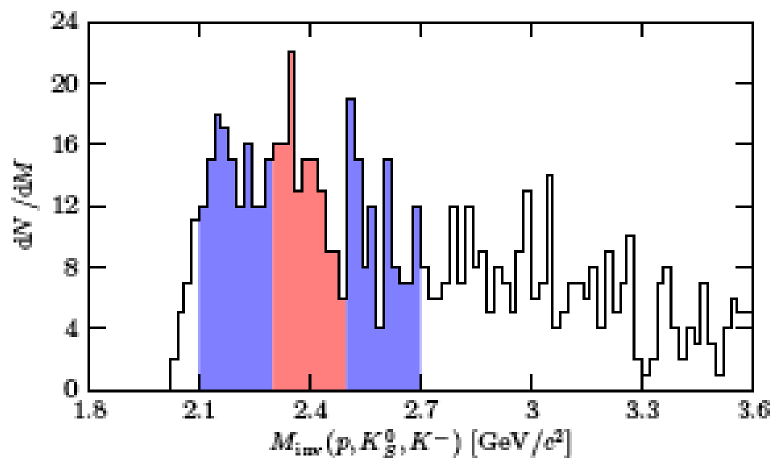
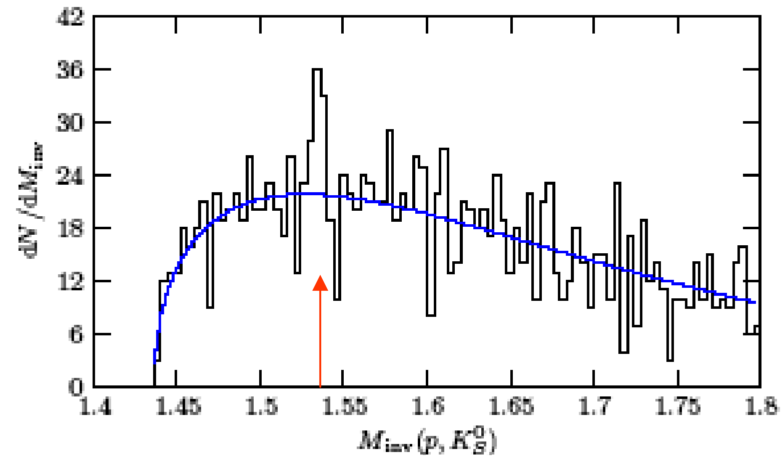
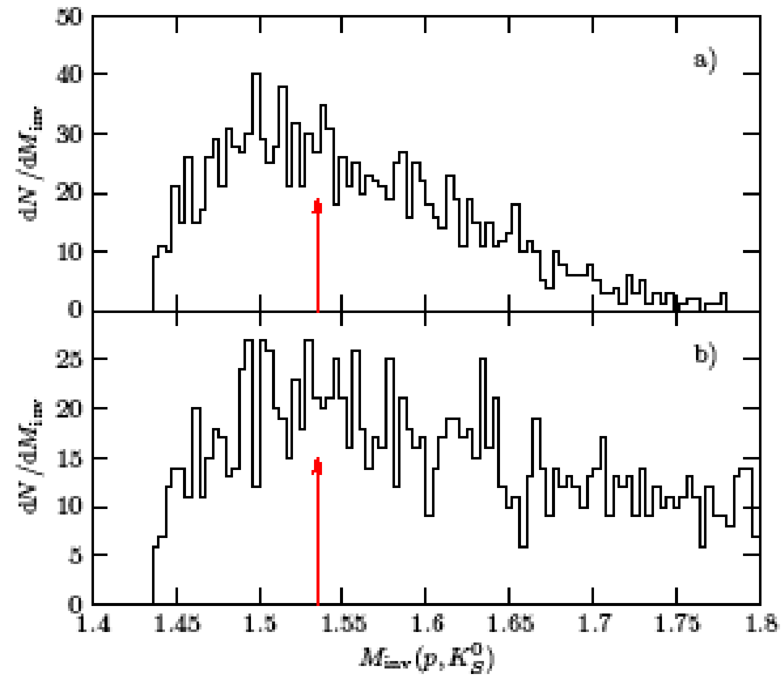


Figure 2: Invariant mass distribution of pK_S^0 pairs in the presence of a K^-







M(p,K^0,K$^-$), if 1.525 M(p,K^0)<1.545 GeV

Conclusions

What is needed for a full success of the N* program?

- More data on polarization observables
    - linearly polarized photons
    - transverse/longitudinally polarized hydrogen and deuterium targets
- Full coupled channel analysis including all final states, in all isospin channels
- Excited Baryon Analysis Center